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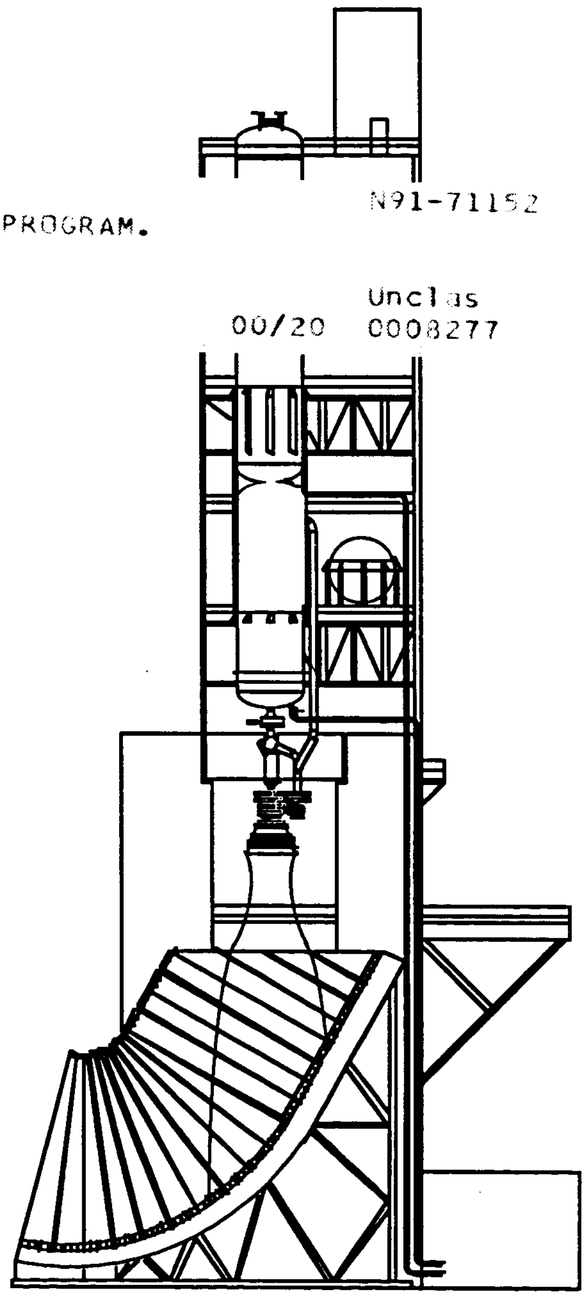
Appendix D
Aerojet Propulsion
Division PTPSTP
Final Report

Propellant Tank Pressurization System Technology Program



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Appendix D, Aerojet Propulsion Division
PTPSTP Final Report

Report Modifications From NASA Review

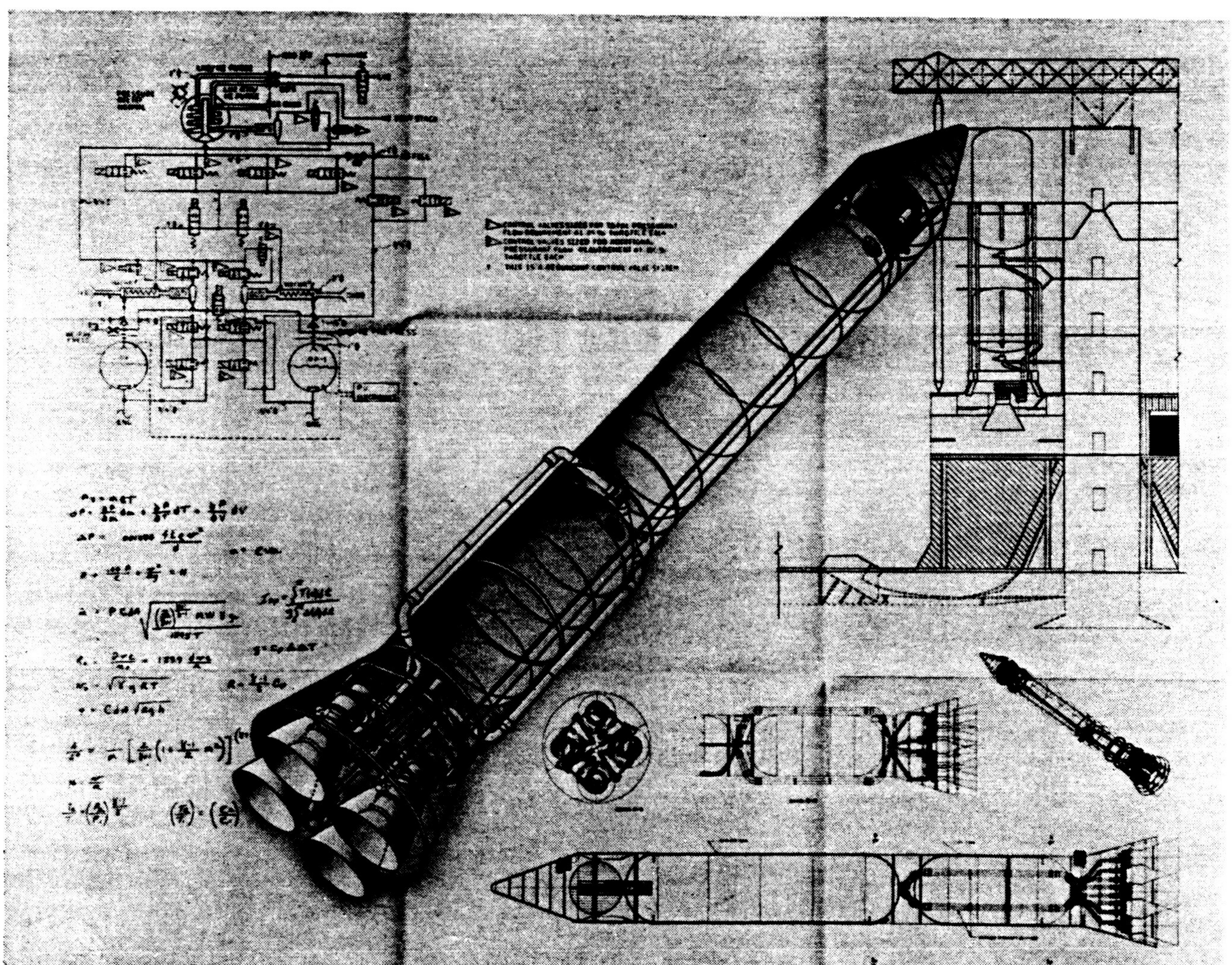
Page	Paragraph	Sentence	Modifications
6	2	2	Replace sentence with: Injector pressure drop requirements were established for a fixed orifice injector at a minimum $\Delta P/Pc$ of 0.06, set at minimum heater flow conditions.
9	3	Last	Replace sentence with: The third flow condition represents the conditions for a failure near the end of the mission where the active heater must be throttled to respond to the failure.
28	1	1	Replace Equation with: $\rho = \frac{PM}{RT}$

Aerojet Propulsion Division

Propellant Tank Pressurization System Technology Program

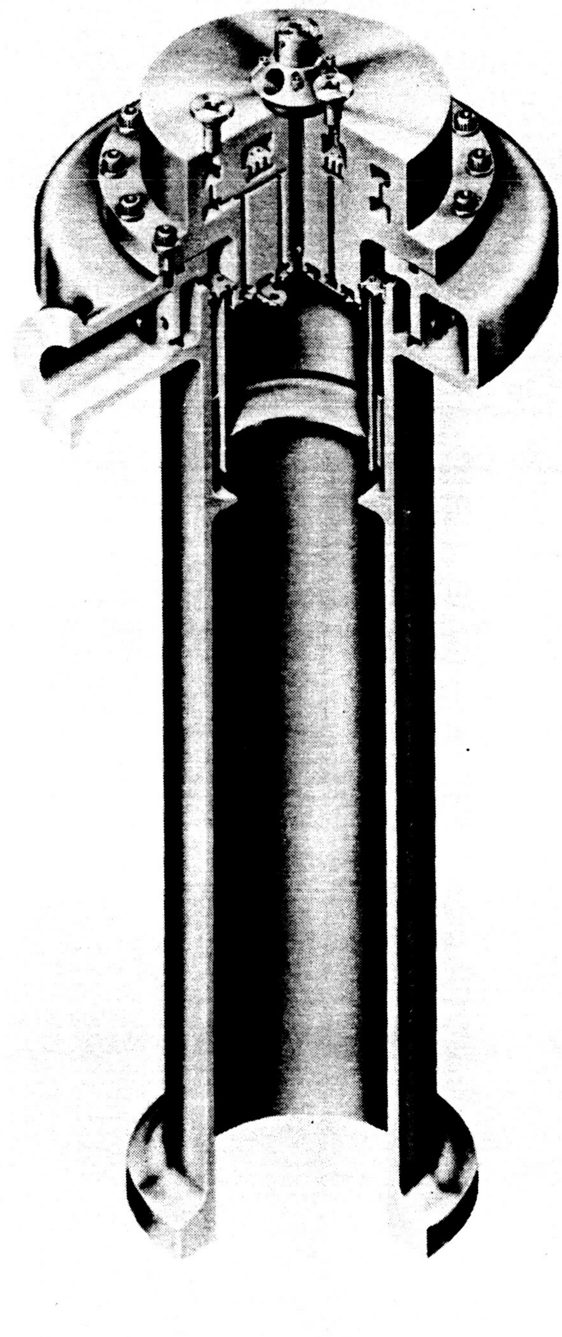
Contract A71364
Final Report
31 August 1990

Prepared For:
Martin Marietta
New Orleans, LA 70189-0514



GENCORP
AEROJET

LOX/LH_2 Helium Heater



PROPELLANT TANK PRESSURIZATION
SYSTEM TECHNOLOGY PROGRAM (PTPSTP)

Contract A71364

Final Report

31 August 1990

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Also the constructive review and criticism of this work that was provided by an Aerojet Design Review Board consisting of Ken Royer, Dick Ewen, Ross Hewitt, Lee Femling, Joe Jellison, and Kent Schaplowsky and their contribution is greatly appreciated.

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I. INTRODUCTION

Martin Marietta Manned Space Systems (MMMSS) has conducted a Pressurization Technology Program under contract NAS 8-37666 for the NASA Marshall Space Flight Center (MSFC). The objective of this effort was to explore, develop, and demonstrate tank pressurization technology applicable to pressure-fed liquid rocket booster (LRB) engines and hybrid propulsion systems for booster application (HRB).

During this activity, a conceptual design study led to the selection of a pressurization system, shown in Figure 1, that provides for heating of supercritical helium (40°R) by mixing with the combustion products (primarily H_2O) from a "stoichiometric" LOX/LH_2 combustor. The LOX/LH_2 combustor, helium injector, and mixing section used to generate a hot (900°R) pressurant gas is noted as the primary heater assembly as shown in Figure 1. A concept for use of this pressurization system within a pressure-fed propulsion system is shown in Figure 2.

The Aerojet Propulsion Division has supported MMMSS in the acquisition and demonstration of the technology required for the direct helium heating pressurization system under subcontract A71364. Aerojet was responsible for the technology acquisition required for the primary heater. As part of this effort, a heater was designed for operation with helium as a pressurant under operating conditions appropriate for a pressure-fed propulsion system as defined by MMMSS.

Technology acquisition for the primary heater would result from design, analysis, and modest specialized subscale testing at Aerojet. Technology demonstration was planned to be accomplished through testing of a primary heater assembly designed and delivered for operation on test stand 116 at NASA's Marshall Space Flight Center (MSFC).

Unfortunately, this program was terminated by NASA in June 1990. At that time, the primary heater concept design was complete and design and analysis in support of a preliminary heater design was underway. This report documents the work accomplished in the design and analysis of the primary heater up to the point of the stop work order (29 June 1990) in accordance with Contract Change Order No. 2, dated 12 July 1990.

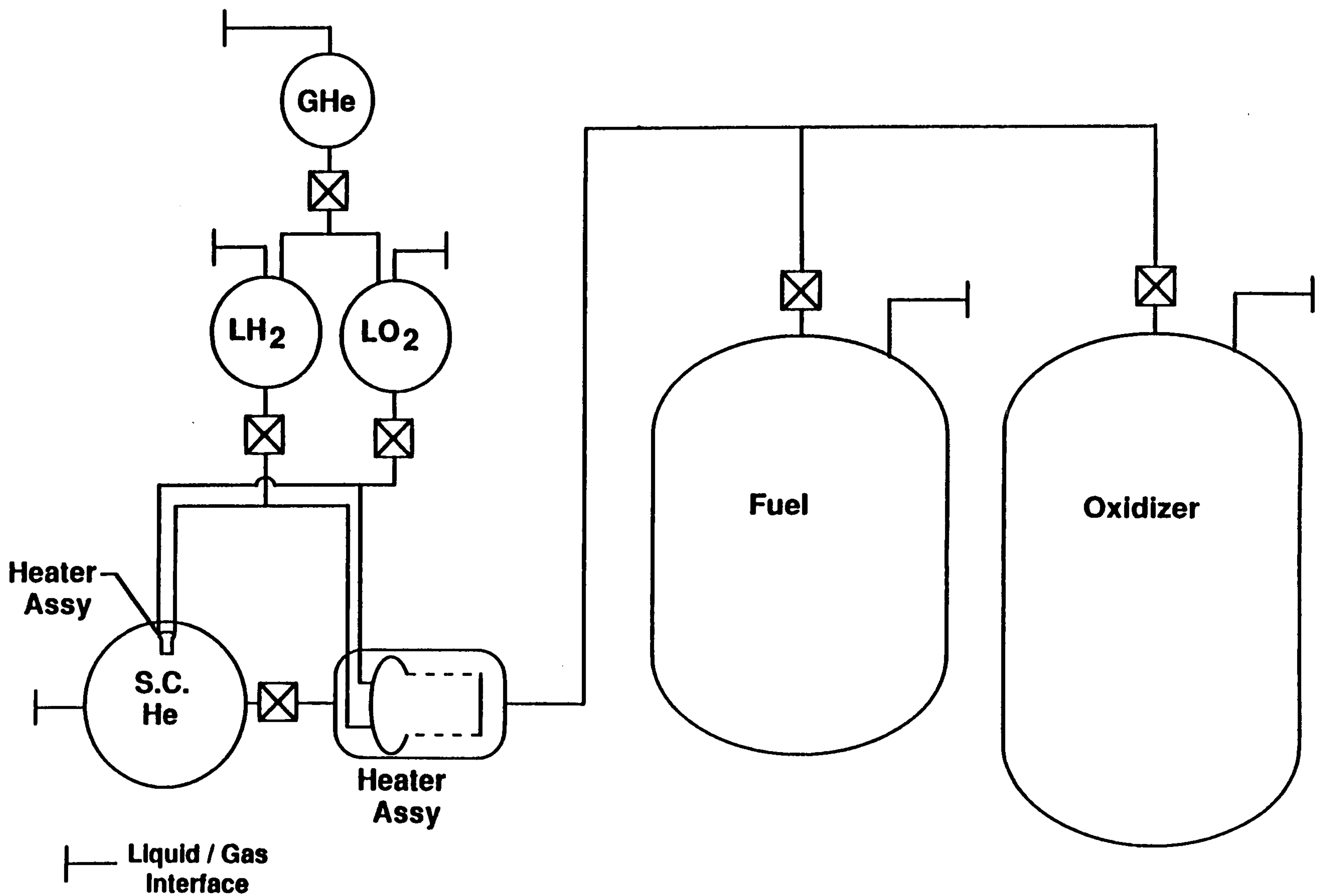

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Figure 1. The Direct Helium Heating Pressurization Concept Uses a Stoichiometric LOX/LH_2 Combustor as a Primary Heating Source

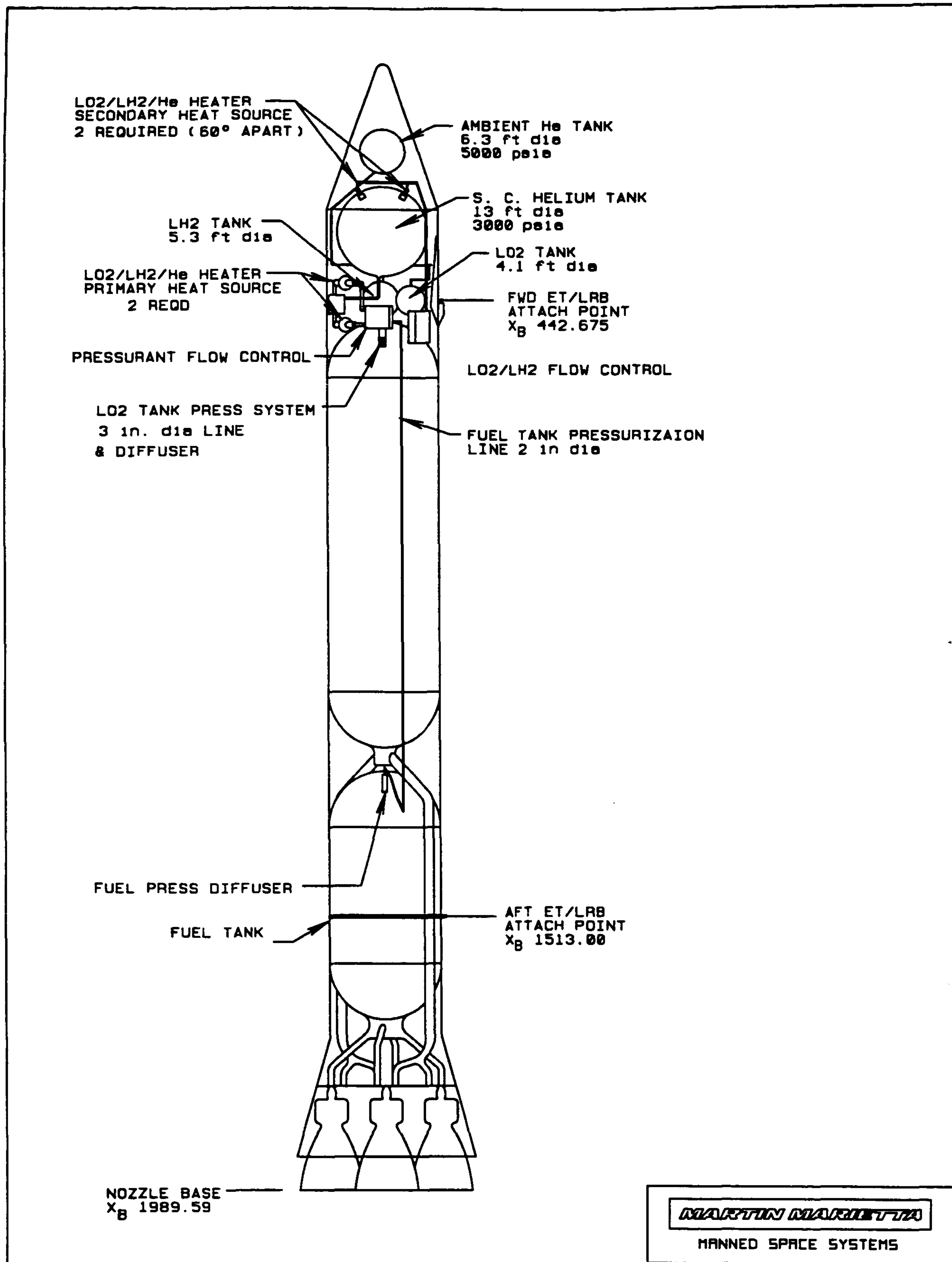


Figure 2. A Pressure Fed Liquid Engine Propulsion Concept Using the Direct Helium Heating Pressurization System

II. SUMMARY

Direct heating of a cold, high pressure helium pressurant using the combustion products from a stoichiometric LOX/LH_2 combustor offers significant system advantages to a pressure fed propulsion system. Included in these advantages are lower system weight, lower life cycle costs, safe and reliable operation and lower technology and hardware development costs. The objective of the work described in this report was the technology acquisition and demonstration for the "primary" heater in this pressurization system. Unfortunately, this work was terminated by direction of NASA early in this technology acquisition phase and thus this report includes only the status of the activity at the time of termination.

This report contains descriptions of the overall approach that was being pursued for technology acquisition and demonstration. This approach included the design, fabrication and delivery of a reduced scale primary heater that was to be test evaluated at NASA's Marshall Space Flight Center on test stand 116. In addition, development of specific technology issues relative to the primary heater were to be accomplished through analysis and simple subscale tests within Aerojet test facilities. These issues included: (1) enhancement of throttling, combustion stability, and thermal protection of the stoichiometric combustor through use of the available helium pressurant flow, (2) demonstration of a LO_2/LH_2 torch igniter within a pressurized, cold helium environment and development, and (3) verification of the combustion and mixing processes within the heater using existing CFD analysis models.

A conceptual design of the primary heater is shown on the frontispiece of this report. The primary heater supplies a heated (800-1000°R) pressurization gas consisting of primarily helium (95-96.5% by mass) and steam (4.3-3.0% by mass) to both a liquid oxygen and a RP-1 propellant tank. This pressurization gas is generated within the heater by mixing cold (40-300°R) supercritical helium with an appropriate amount of combustion products (steam) from a stoichiometric LOX/LH_2 combustor. The stoichiometric combustor throughput is controlled by regulation of the LOX and LH_2 inlet pressure using a flow control system based on feedback of the primary heater mixed pressurant temperature. Helium flow to the heater is regulated by a control system based on tank pressure feedback. Preliminary design requirements result in LOX and LH_2 flow variations over nearly a 4:1 range and helium flow variation over a 2.6:1 range while supplying a tank pressure of 1450 psia.

Major components for the primary heater include a LOX/LH_2 injector, a LOX/LH_2 torch igniter, a combustion chamber with or without an isolation sleeve to preclude combustion quenching by the cold helium, a helium manifold and injector, and a mixer consisting of a straight pipe section with or without a mixing ring. The cold helium enters the heater through a single inlet and is distributed in an outer annulus surrounding the stoichiometric LOX/LH_2 injector. The helium is injected into the heater in an annular flow surrounding the hot combustion gases. The helium provides thermal protection in the combustion zone and then mixes with these gases after combustion is completed. This mixing is induced by shear between the streams and by the mixing ring, if required.

This conceptual design was developed from previous experience in the design of liquid propellant combustion chambers and preliminary design analyses. Supporting analyses in the fields of computational fluid dynamics (CFD), thermal and combustion processes were underway at the time of program termination and are reported herein to the extent completed at that time.

An analysis of the mixing process between the hot combustion products and the cold helium was performed using the FLUENT CFD code developed by CREARE Inc. This code solves the transport equations for mass, momentum, energy, and chemical species using a finite-difference technique. A simplified mixing analysis of three mixing concepts was performed using FLUENT. The results showed that adequate mixing could be achieved within a coaxial mixer having an L/D of approximately 20:1. Use of a mixing ring to induce turbulence could significantly reduce the required mixing length but would require additional pressurant ΔP. Radial injection was shown to also promote mixing similar to a turbulence ring. Since the turbulence ring was a simple extension of the coaxial mixer concept it was recommended that the more complex radial injection concept be dropped from further consideration.

A rigorous analysis using an improved version of FLUENT was in work at the time of program termination. Further work with this code is recommended to support the primary heater technology development. Validation of the code could be accomplished with existing experimental data as described in Section IV,D,1,d of this report. Application of this code to future heater design efforts would supply insight into the mixing and combustion processes and guide the design development in terms of combustion product/helium interaction, chemical kinetics, and mixer design and pressure drop requirements.

A preliminary thermal analysis was performed to define the helium flow required to "film cool" the LOX/LH_2 combustor and to estimate the LOX/LH_2 injector face thermal capability. The results of the film cooling analysis indicated that the combustor wall temperature could be maintained at 1000°F or less through the use of no more than 7% of the total helium flow. A thermal analysis of the zirconium copper injector faceplate indicated that a maximum steady state temperature of less than 600°F was expected even with a relatively coarse injector element pattern. Results of these thermal analyses are included in Section IV,D,2 of this report.

Finally, a combustion analysis was performed to define the essential features of the stoichiometric LOX/LH_2 injector and combustion chamber. Injector pressure drop requirements were established for a fixed orifice injector at a minimum $\Delta P/Pc$ of .06. This results in an inlet pressure requirement of almost 3000 psi at the maximum heater flow condition. A coarse (relatively high flow/element) injector pattern was established consisting of six elements (two LOX and two hydrogen orifices per element) to ensure stable combustion without the use of acoustic damping devices. A combustor length of approximately 4 in. was recommended to achieve an energy release efficiency greater than 90%. Also an isolation sleeve was recommended in this combustion region to preclude quenching of the combustion by the cold inert helium.

These combustor design and operating parameters are based on current available technology and do not consider possible favorable advantages in the use of the large quantity of helium in control of the combustion process. It has been hypothesized that the presence of an inert gas barrier at the perimeter will be beneficial from a combustion stability standpoint in terms of both throttling (chug stability) and high frequency acoustic instability. Investigation of this potential was a key technology extension under study during this program. This and other technology issues identified for evaluation and demonstration during this program are discussed in Section IV,E of this report.

III. CONCLUSIONS AND RECOMMENDATIONS

Technology for the design and development of a direct helium primary heater using a stoichiometric LOX/LH_2 combustor is available and in-place. Further development of this technology, particularly in the area of ignition and utilization of the helium to extend or enhance the LOX/LH_2 combustor stability is recommended to provide for a simpler heater design with higher reliability and lower cost. Simplified, subscale and subcomponent testing using modest and possibly existing hardware would provide a cost effective means for this technology development.

The FLUENT CFD computer code has been demonstrated as a powerful tool for the analysis and design support of the helium heater. Further application of this code and validation of its capabilities using existing experimental data bases is recommended.

IV. TECHNICAL DISCUSSION

This section contains descriptions of the overall approach that was being pursued for the technology development and demonstration of a primary heater for application to pressurization systems for large pressure fed propulsion devices. The primary heater is used for heating of supercritical helium (40°R) by mixing with the combustion products from a stoichiometric LOX/LH_2 combustor.

This approach included design, analysis, and specialized heater component testing at Aerojet and the fabrication and delivery of a reduced scale primary heater that was to be test evaluated at NASA's Marshall Space Flight Center (MSFC) on test stand 116.

Design requirements developed for this test demonstration hardware are provided as well as a description of the design concept. Supporting design analyses for the mixing, thermal and combustion processes within the heater are presented to the extent completed at the time of the stop work order (29 June 1990). Finally, the technology issues that have surfaced and were being pursued are summarized.

A. PRIMARY HEATER TECHNOLOGY DEMONSTRATION OVERVIEW

Acquisition and demonstration of the technology required for the direct helium heating pressurization system was to be achieved through the design, fabrication, development, test, and delivery of pressurization system components sized for a pressure-fed breadboard system currently under design at MSFC. Aerojet was responsible for the technology acquisition required for the primary heater. This heater was designed for operating with helium as a pressurant and operating conditions appropriate for a pressure-fed propulsion system were defined by MMMSS. Aerojet was to design, fabricate, and test primary heater components, subassemblies and/or assemblies to the extent necessary to acquire the needed technology.

Testing at Aerojet was planned to develop and demonstrate specific portions of the technology needs identified for the primary heater. These technology issues are discussed in Section IV,E of this report and include items such as ignition within a pressurized cold helium environment, mixing, and combustion efficiency within the heater, and utilization of the helium for enhancement of stoichiometric combustor combustion stability and extension of its throttling limit. The Aerojet testing for development of this technology would be accomplished with modest scale hardware using existing components where possible.

Technology demonstration of the entire primary heater concept would be accomplished through testing of a heater assembly designed and delivered for operation on test stand 116 at MSFC. This technology demonstration for the primary heater on test stand 116 was planned using hydrogen in place of helium on selected tests as the primary pressurant. This substitution was considered because of the expense of hardware required to condition helium to supercritical temperatures and pressures and the recurring high cost of helium for each test run. However, any deviation from the basic design for helium to accommodate hydrogen for this demonstration was not desirable and such deviations, if required, would be thoroughly evaluated.

Approximately three months of effort was accomplished towards completion of this activity at the time of the stop work order. Design requirements were established and a Design Requirements and Conceptual Design Review was conducted. A description of these accomplishments are included in the following sections.

B. DEMONSTRATION HARDWARE DESIGN REQUIREMENTS

A set of design requirements for the demonstration primary heater were developed based on input and criteria received from MMMSS. These design requirements are provided in Table I and are representative of a pressure-fed liquid engine propulsion system operating over a 120 second pressurization cycle. The system is sized for a maximum helium pressurant flowrate of 30 lbm/sec, which is sufficient to pressurize both oxygen and RP-1 tanks to 1350 psia when operating a pressure-fed liquid rocket booster that generates 750,000 lbf of thrust. Three pressurant (helium) inlet flow conditions are included in Table I to define operating extremes for design purposes. The first inlet flow condition (maximum), represents the maximum helium flow requirement corresponding to a heater out condition early in the pressurization cycle. The second inlet flow condition (minimum), represents normal heater operation at the end of the pressurization cycle. The third flow condition (maximum delta pressure) represents the case for maximum flow with minimum helium inlet pressure that would occur with heater out operation (maximum flow) at the end of the pressurization cycle (minimum inlet pressure).

TABLE I

Primary Heater Design Requirements for Technology Acquisition

- Pressurant (Supercritical Helium)
  Maximum Flow Conditions
  - Flowrate = 30 lbm/sec
  - Inlet Temperature = 40^{o}R
  - Inlet Pressure = TBD psi (APD)

  Minimum Flow Conditions
  - Flowrate = 11.4 lbm/sec
  - Inlet Temperature = 300^{o}R
  - Inlet Pressure = TBD psi (APD)

  Critical Inlet Flow Condition
  - Flowrate = 22.8 lbm/sec
  - Inlet Temperature = 300^{o}R
  - Inlet Pressure = 1550 psi

- Heating Source
  - LO2/LH2 Combustor
  - Mixture Ratio (O/F): 8:1 + TBS (APD)
  - Inlet Pressure: TBS (APD)
  - Inlet Temperature: LO2 = 163^{o}R; LH2 = 50^{o}R
  - Flowrate: TBS (APD)

- Heater Exit Conditions
  - Exit Bulk Temperature
    - 900^{o}R $\pm$ 100^{o}R
    - Temperature Uniformity: Sufficient to meet life reqirements
  - Exit Pressure: 1450 psi
  - Maximum Exit Mach Number: 0.3

- Heater Start Conditions
  - Pressure: 1350 psi (Helium Lockup)
  - Temperature: 300 - 350 ^{o}R

- Interface Requirements
  - Helium Inlet I.D. = TBS (APD)
  - Inlet and Outlet Connector: Grayloc Flanges
  - LH2 and LO2 Inlet Line Size: TBS (APD)

- Structural Margin: 2.0 Factor of Safety Based on Yield Properties @ Maximum Operating Temperature (1200^{o}R Goal)

- Life: 50 Pressurization Cycles without Rework. 120 sec duration for each Pressurization Cycle.

The equivalent operating requirements for the technology demonstration on MSFC test stand 116 are provided in Table II. Note that the operating requirements provided in Table II are intended to be achieved using the primary heater that meets the design requirements in Table I. Any deviation from this basic design for helium to accommodate hydrogen must be evaluated by Aerojet and approved by MMMSS.

C. DESIGN DESCRIPTION

An illustration of the helium primary heater design concept is shown in Figure 3. Major components for the heater include a LOX/LH_2 injector, a LOX/LH_2 torch igniter, a helium manifold and injector, the combustion chamber with a removable pressurant isolation sleeve and a mixing section with an adjustable height mixing (turbulence) ring. An artists conception of a flight-type primary heater is shown on the frontispiece of this report. The deliverable heater for technology demonstration testing at MSFC would be similar in design except it would contain additional flanges for ease in adjustment and/or replacement of heater components and instrumentation ports for pressure and temperature measurements for empirical characterization of the heater operation.

Liquid oxygen and liquid hydrogen inlets are contained on the body of the injector where the reactants are distributed through a manifold system for injection into the combustion chamber. The inlet pressure to the injector is regulated by a flow control system based on feedback of the primary heater mixed pressurant temperature. The cold pressurant (helium at 40 to 300°R) enters the heater through a single inlet and is distributed in an outer annulus surrounding the stoichiometric LOX/LH_2 injector. The helium is injected as an annular stream surrounding the hot combusting gases. The helium provides thermal protection in the combustion zone and then mixes with these gases after combustion is completed. This mixing is induced by shear between these streams and by a mixing ring (if required).

1. Stoichiometric LOX/LH_2 Injector

A cross-section view of the injector conceptual design is shown in Figure 4. The injector is a welded stainless steel assembly that bolts to the mixer flange, holding the helium flange in place. A zirconium copper monoplate face is brazed to the injector body using a proven braze methodology. The liquid oxygen is fed through a

TABLE II

Primary Heater Operating Requirements for Technology Demonstration on MSFC Test Stand 116

- Pressurant (Hydrogen)

  Hydrogen flow conditions to be adjusted to match the (Helium) combustor flow rates at each design point.

- Heating Source

  Same as Table I - The H2 pressurant simulant flowrate is adjusted so that critical mixing parameters will match that required for helium. Changes in reactant inlet conditions, if any, are TBD (APD)

- Heater Exit Conditions

  Same as Table I - Except changes in minimum temperature, uniformity and exit pressure resulting from the use of H2 pressurant simulant are TBD (APD)

- Instrumentation

  Design consideration shall be made to provide instrumentation adequate to determine and verify satisfactory primary heater operation - TBD (APD).

- Test Demonstration

  To be conducted on test stand 116 at the NASA MSFC. Tests to demonstrate critical operating points under steady state conditions over the primary heater required operating range.

  Approximately 20 tests are planned including the following:

  - System Flow Testing (5 tests)
    Establish system resistance and valve flow characteristics, fill and response times

  - Open Loop Throttle Testing (10 tests)
    Single point testing at critical combinations of pressurant flow, inlet pressure and temperature

  - Closed Loop Testing
    System simulation and verification

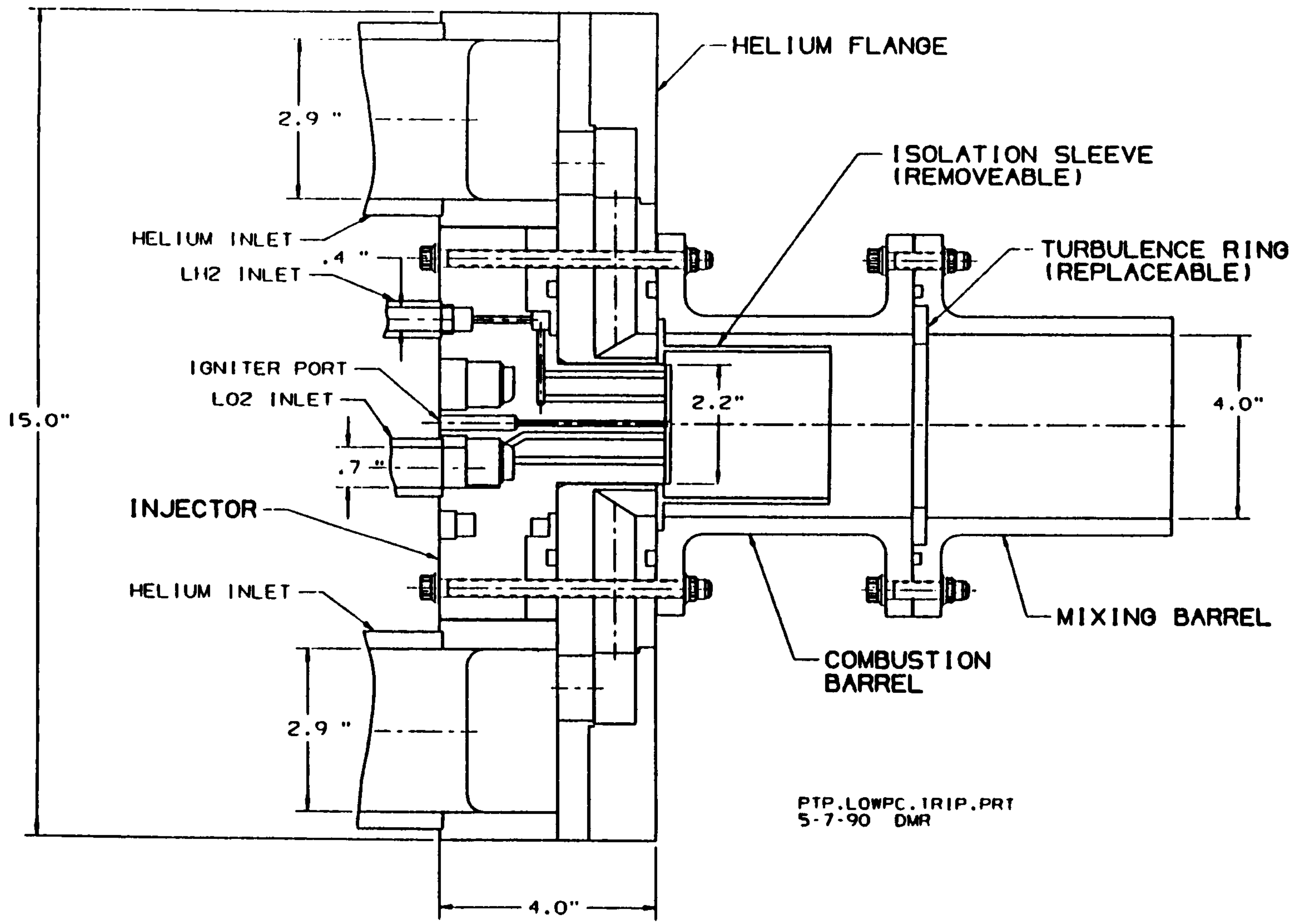


Figure 3. A Conceptual Design for the Helium Primary Heater

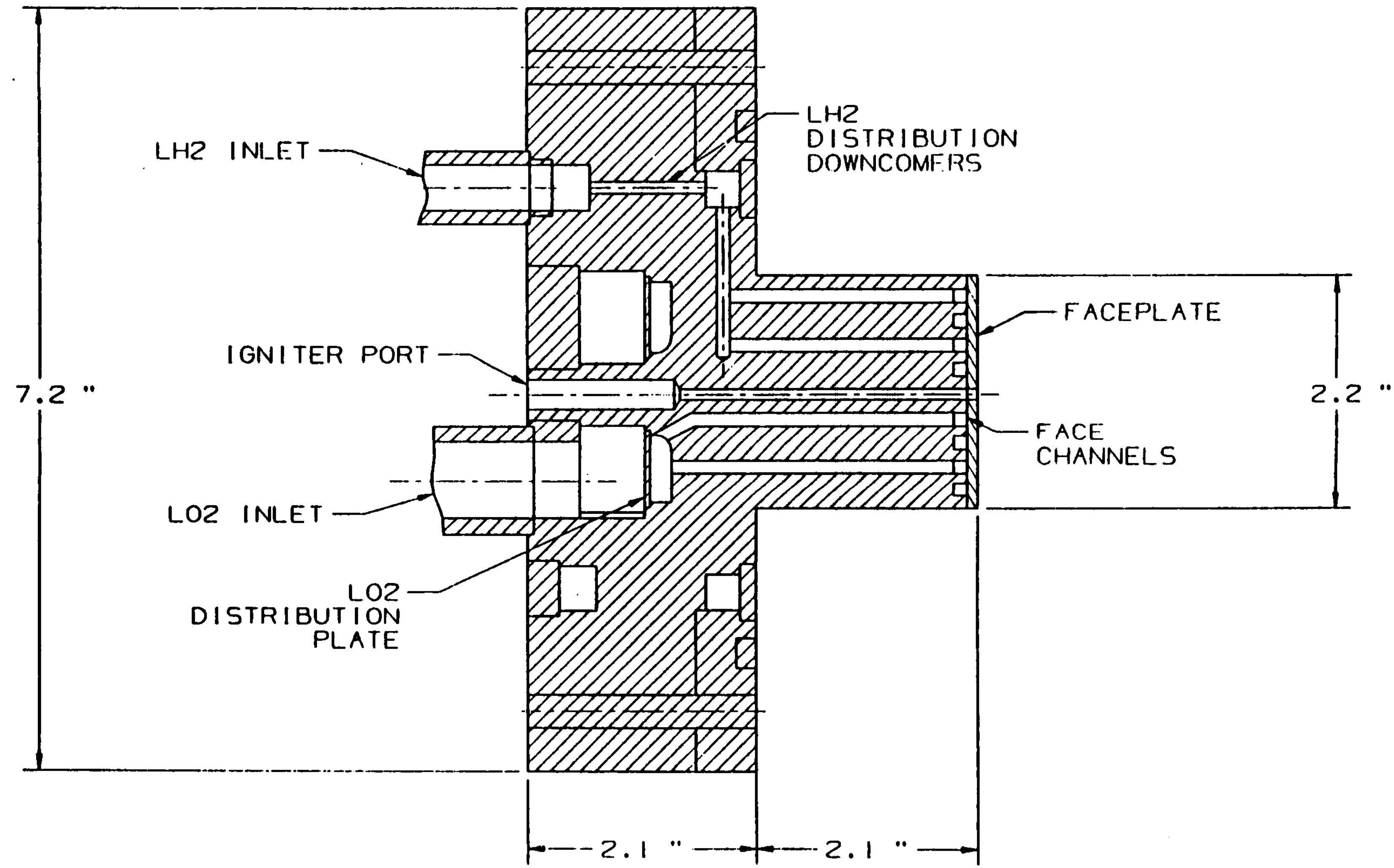


Figure 4. The Stoichiometric Lox/LH_2 Injector Assembly Is Based on Conventional Liquid Propellant Injector Design Features

single inlet into two manifolds, separated by a distribution ring, through axial downcomers to concentric channels feeding the face plate's oxidizer orifices. The hydrogen is similarly fed through a single inlet into a manifold, through downcomers distributing the flow into another manifold, into radial cross drilled passages, and through axial downcomers to the concentric channels feeding the face plate's fuel orifices. Propellant manifold flow distribution devices are used to ensure a uniform pressure distribution to the backside of the injector faceplate containing the injector elements.

The injector faceplate is made from zirconium copper and contains a relatively coarse six element pattern. The elements are arranged in a circular pattern as shown in Figure 5. Each element consists of a self-impinging liquid oxygen doublet and two liquid hydrogen orifices arranged to impinge on the ends of the developing LOX doublet fan. In concept, this element is similar to a conventional FOF triplet element with the center oxygen orifice replaced by the self-atomizing LOX doublet. The LOX orifice diameter is 0.063 in. and the hydrogen orifice diameter is 0.044 in. The orifice sizes were selected to achieve stable combustion in both the high frequency and chug modes over the required throttling range.

Historic data, throttleability, compatibility, mixing and cost were also considered as the injector element selection criteria. These criteria were examined and doublet/quadlet, triplet and showerhead elements were evaluated. Both showerheads and FOF triplets were eliminated due to their poor mixing (FOF triplet's oxidizer diameter would have to be twice the fuel diameter for equal pressure drop). Vaporization and/or mixing is adversely affected with OFO triplets because an oxygen periphery would result that allows the helium to move into the core more easily than a hydrogen boundary. Canted like doublets were initially baselined because they have the most extensive theoretical and empirical characterization for LO_2/LH_2. The resultant pattern was very coarse: 10 elements with 0.05 inch diameter orifices. The Extended Temperature Range (ETR) program had a similar coarse face pattern and found that the combustion efficiency was a strong function of length (Ref. 1). The injector's coarse pattern would provide an environment conducive for helium to interfere with the O_2/H_2 reaction, so emphasis has been placed on developing an element with good intra-element mixing. Conventional canted like doublet elements impinge the fuel and oxidizer fans edge-on-edge, leaving lobes of unmixed propellants. The candidate element design

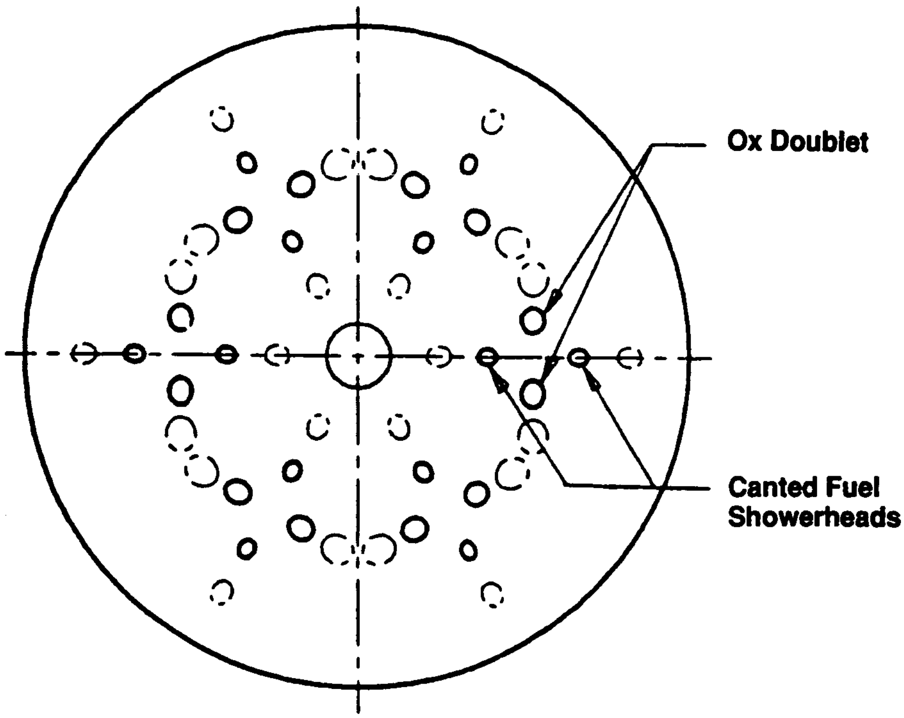


Figure 5. The Injector Faceplate Contains a Relatively Coarse Six Element Pattern

is a potential improvement since one fuel stream impinges on either edge of the oxidizer fan. This element acts more like a triplet but does not have the orifice diameter difference that the FOF would require or the OFO's adverse effect on vaporization and mixing. More details on the element selection, stability, and performance can be found in Section IV,D,2 of this report.

2. Igniter

The igniter, shown in Figure 6, is a LOX/LH_2 torch consisting of a modified aviation type spark plug with separately plumbed fuel and oxidizer lines providing an oxidizer rich flame through the core. It fits through the center of the injector core and is modified from the Orbital Transfer Vehicle (OTV) (Ref. 2) design which operated with GO_2/GH_2 at a similar pressure regime. The O_2 is injected through a metering washer onto the spark electrode tip where it is energized. The hydrogen flow is split with a fraction being injected through another metering washer and into the energized oxidizer stream forming the core flow. The rest of the hydrogen is fed between the liner and chamber for cooling and then dumped into the core flow. The mixture then continues to flow through the face and into the combustor where the main injector elements are ignited. The components are assembled and bolted together onto the injector. Material selection has not been completed but consideration will be given to high conductivity materials that are acceptable in this hydrogen environment.

Oxygen and hydrogen have been used extensively in torch ignition as noted in Figure 7, but most experience is with gaseous propellants. The ETR program successfully tested with LOX/LH_2 and the ALS program is baselining the flight system with liquids. Hypergolics were also considered for the helium heater ignition system. They are very simple to use but were ruled out to avoid an extra tank on the vehicle and to preclude possible downstream tank contamination.

Technology for LOX/LH_2 torch igniter design and operation is established. However, igniter operation within a cold helium pressurized environment has not been demonstrated. Issues in terms of igniter sequencing, spark energy, and ignition propagation must be resolved.

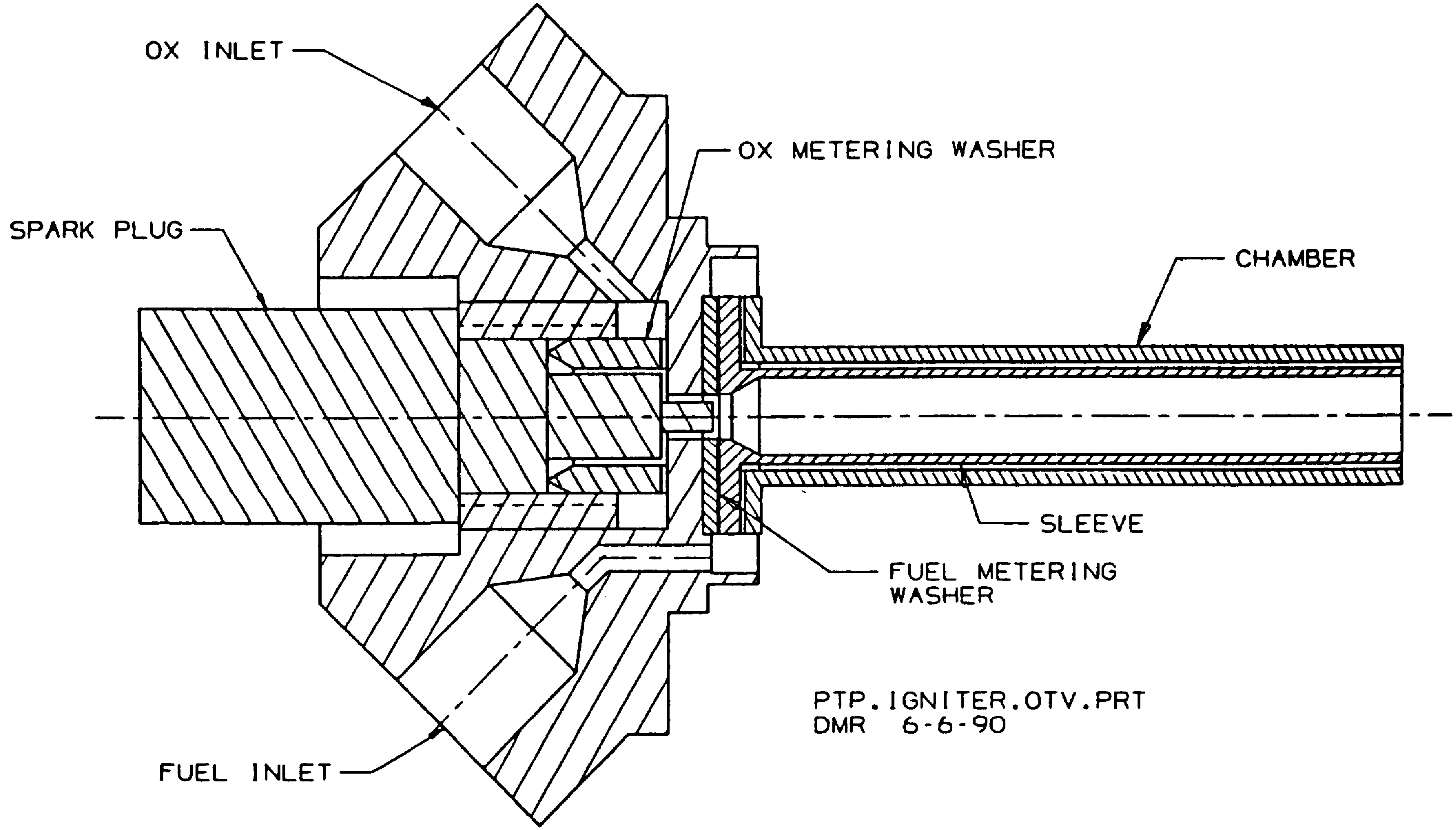


Figure 6. Torch Igniter Design Concept

	Barrel dia., in.	Flowrate, lbm/s	Mixture Ratio	Spark Rate, sps	Spark Energy, MJ	Gap Width, in.	$\frac{\dot{W}\ \text{igniter}}{\dot{W}\ \text{chamber}}$
ETR (L/L; G/L; G/G)	0.25	0.120	5.0	500	10	0.050	–
ITA (G/G)	0.30	0.083	45 Core 6.5 o/a	500	100	0.030	2.3%
OTV (G/G)	0.25	0.0042	46 Core 3.6 o/a	300	10	0.030	0.07%
OX/Fuel Rich Preburner (G/G)	0.25	0.090	3.5	500	30	0.030	0.2%
Carbon Deposition (G/G)	0.40	0.185	45	500	30	0.030	1.3%
Cryo 500 (G/G)	0.30	0.0065	5.0	500	10	0.030	0.6%
ADPGG (L/L, G/G)	0.30	0.115 at ignition	81 Core 0.8	500	TBD	avg = 0.81%, 3σ = 2.76% 0.030	1%

M16/D14/Fig-6

Figure 7. Igniter Historical Data

Aerojet tests with helium back pressure are planned where ignition limits are defined in terms of pressure, flowrates, sequencing, and spark energy. Ideally, the tests would be conducted using the heater injector characterization test assembly, but a low cost alternative would be to use existing ETR hardware at the lower operating pressure to understand the ignition envelope and required start sequence.

3. Helium Flange

The stainless steel helium flange bolts between the injector and mixer (Figure 3) with Teflon coated raco face seals protecting the joints from cryogenic propellant leakage. The proposed removable combustion zone isolation sleeve would fit between the helium flange and the mixer assembly. Helium is fed through two inlets, into two manifolds separated by distribution holes, through radial drilled passages and into an annulus. Flow is metered with the combustion zone isolation sleeve, if used, and injected axially on either side of the sleeve and into the mixer. The flow passages are sized for the critical pressure flow case so that the helium pressure drop through the manifold and mixer does not exceed 100 psi.

4. Combustion Chamber

In the present design concept, the combustion chamber for the primary heater is bounded by a helium cooled isolation sleeve noted in Figure 3. The isolation sleeve length is established so that nearly complete combustion of the LOX/LH_2 propellants is achieved before mixing with the helium pressurant is induced. The isolation sleeve is used to preclude adverse mixing of the helium with the LOX/LH_2 before combustion is complete. Such mixing may quench the combustion and result in poor heater efficiency and introduction of combustible products into the respective fuel and LOX tanks that are being pressurized.

The requirement for the isolation sleeve is a technology development and demonstration issue. Elimination of the sleeve would simplify the combustor design resulting in lower cost and improved heater reliability. Also, the presence of a compliant non-reactive outer barrier in the combustion chamber may significantly enhance the stability of the combustion and reduce the injection pressure drop required for chug free operation.

5. Heater Mixing Section

The mixing section of the helium heater, shown in Figure 3, consists of a straight pipe section containing a central stream of hot combustion gases surrounded by an annulus of cold helium pressurant. The mixer contains two sections separated by a bolted flange that contains a removable mixing ring. The height of the mixing ring can thereby be varied to obtain a tradeoff of mixing uniformity and mixer length with mixer pressure drop.

Mixing is induced through shear between the hot gas stream and the helium pressurant flow. The mixing ring further enhances mixing through turbulence generation.

This is a fairly low pressure drop system that utilizes length to accomplish the required mixing. Trade studies were conducted where many mixing concepts were evaluated and selection criteria identified. The criteria used to select the mixing concept were pressure drop, cost, mixing uniformity, reliability, and risk. Coaxial injection, radial injection and turbulence rings were selected for preliminary evaluation. The FLUENT CFD code was used to compare the three concepts and it was found the pure coaxial mixing took the longest length to mix as expected. Radial injection or use of a turbulence ring were about equal in the required mixing length reduction when used with the coaxial injection. Cost and simplicity led to the selection of mixing with a downstream turbulence ring.

D. SUPPORTING ANALYSES

The conceptual design described in the previous section is based upon previous experience in the design of liquid propellant combustion chambers and preliminary design analyses. Three major areas of supporting analyses include (1) CFD analysis of the mixing and chemical kinetic processes, (2) thermal analysis, and (3) combustion stability and performance. The approach and results of these supporting analyses are described in this section.

1. CFD Analysis

An analysis was made using the computer code FLUENT (Ref. 3) to calculate the exit temperature profiles and the pressure drops in the heater for the three mixing concepts. The intent is to determine a mixing concept that provides more mixing (uniform exit gas temperature and composition) with less pressure drop. This section contains a description of the analysis approach, the computer code used in the analysis, and the calculated results.

a. Description of Computer Code FLUENT

The computer code FLUENT is a commercial computational fluid dynamics (CFD) program developed by CREARE Inc. for modeling fluid flows. This computer code is capable of calculating steady or unsteady, compressible or incompressible, single phase or multiphase, reacting or non-reacting, laminar or turbulent, two-dimensional (including axisymmetric) or three-dimensional flows. The code was recently acquired by the Aerojet Propulsion Division and has been applied in several projects at Aerojet. The code solves the transport equations for mass, momentum, energy, and chemical species using a finite-difference technique.

Two versions of FLUENT, 2.99 and 3.02, were used in the present analysis. Version 3.02 has several improvement features in user interface as well as in physical modeling approach. The new version is capable of handling multistep reaction and calculating mixture properties from individual component properties. Version 2.99 was used for most of the analysis described herein because version 3.02 was not yet available.

b. Analysis Approach

Three mixing concepts were proposed for the primary heater design. Early selection of a mixing concept will obviously reduce the design and analysis efforts. The approach taken, therefore, was to conduct a preliminary analysis to evaluate the relative the mixing and pressure drops between the three concepts to make a down selection based on the analysis results. Since only relative results between the three concepts are needed, the analysis was greatly simplified. The analysis was made with preliminary definition of combustor/mixer geometry and operating conditions using FLUENT version 2.99. It was assumed that changes in heater dimensions and operating conditions will not significantly affect the relative results between the three designs evaluated. Once a mixing concept is selected and the operating parameters and combustor/mixer geometry are better defined, a detail analysis must be performed using the updated version of FLUENT to calculate more accurately the pressure drop, and the exit profiles of Mach number, temperature, and chemical species concentrations. These calculated results can then be used to verify the specified design requirements.

c. Analysis Results

Three concepts of mixing helium gas with LOX/hydrogen combustion products were evaluated: 1) coaxial flow of the helium, 2) coaxial flow of the helium with a turbulence ring, and 3) radial injection of the helium. These mixing concepts are shown schematically in Figure 8.

Preliminary analyses for qualitatively evaluating the three mixing concepts were made using FLUENT 2.99. The geometries and operating conditions used in this preliminary analysis are shown in Figures 9 to 11. In this analysis, combustion of oxygen and hydrogen are assumed to be completed. Thus, the analysis only evaluated the mixing of the cold helium gas with the combustion products. A more detail analysis which simultaneously accounts for the mixing and reaction of helium, oxygen, hydrogen, and combustion products can be performed after a mixing concept selection has been made.

After the preliminary analysis was initiated, the operating pressure was changed from 2950 to 1450 psia as a result of the change in the location of the pressure regulator downstream to upstream of the heater. The heater diameter was also increased to 4 inches to increase margins on the exit Mach number and pressure drop. No updated analysis was made, however, because changes in operating pressure and chamber diameter should not effect the relative results between the three mixing designs.

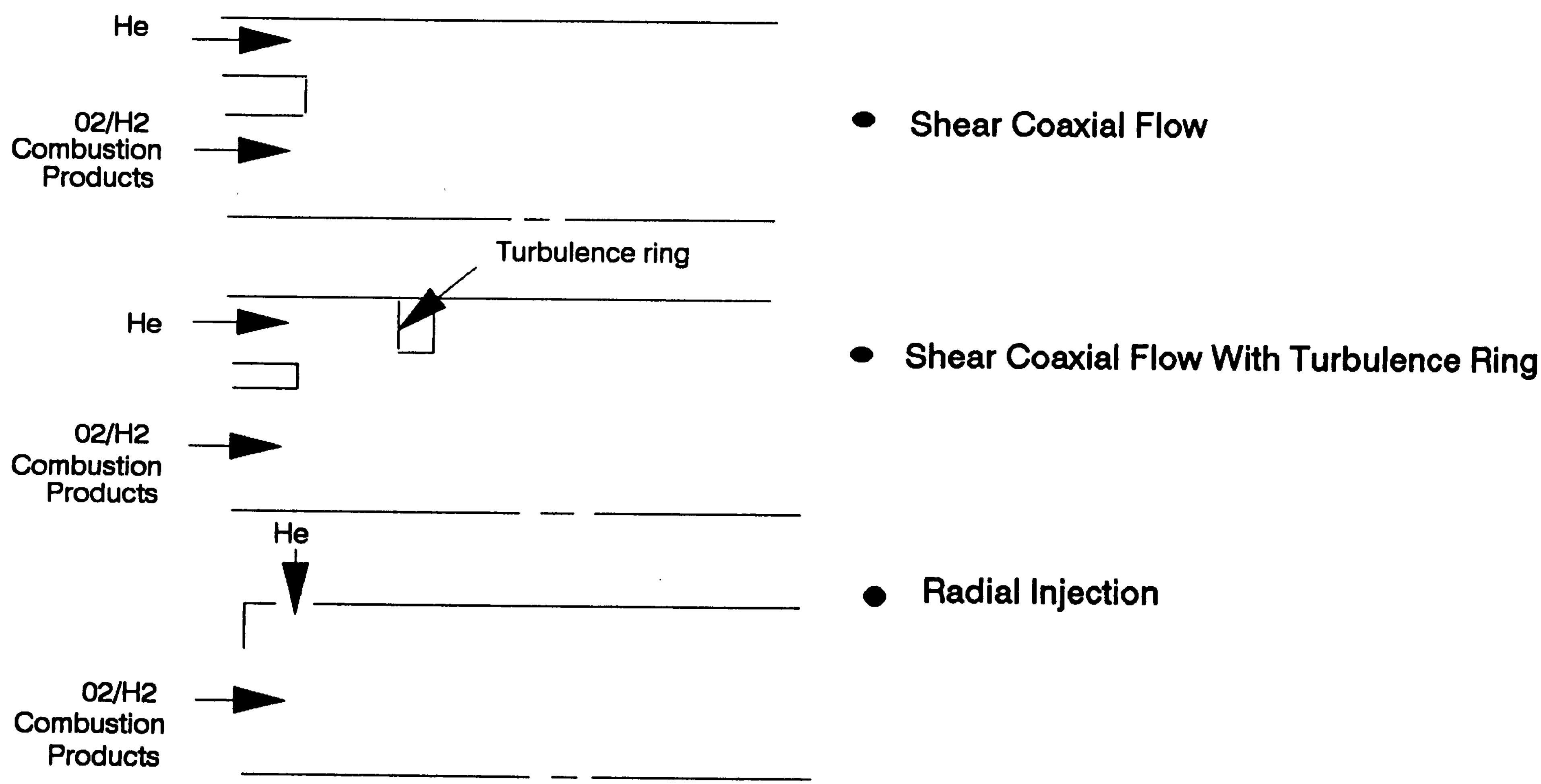
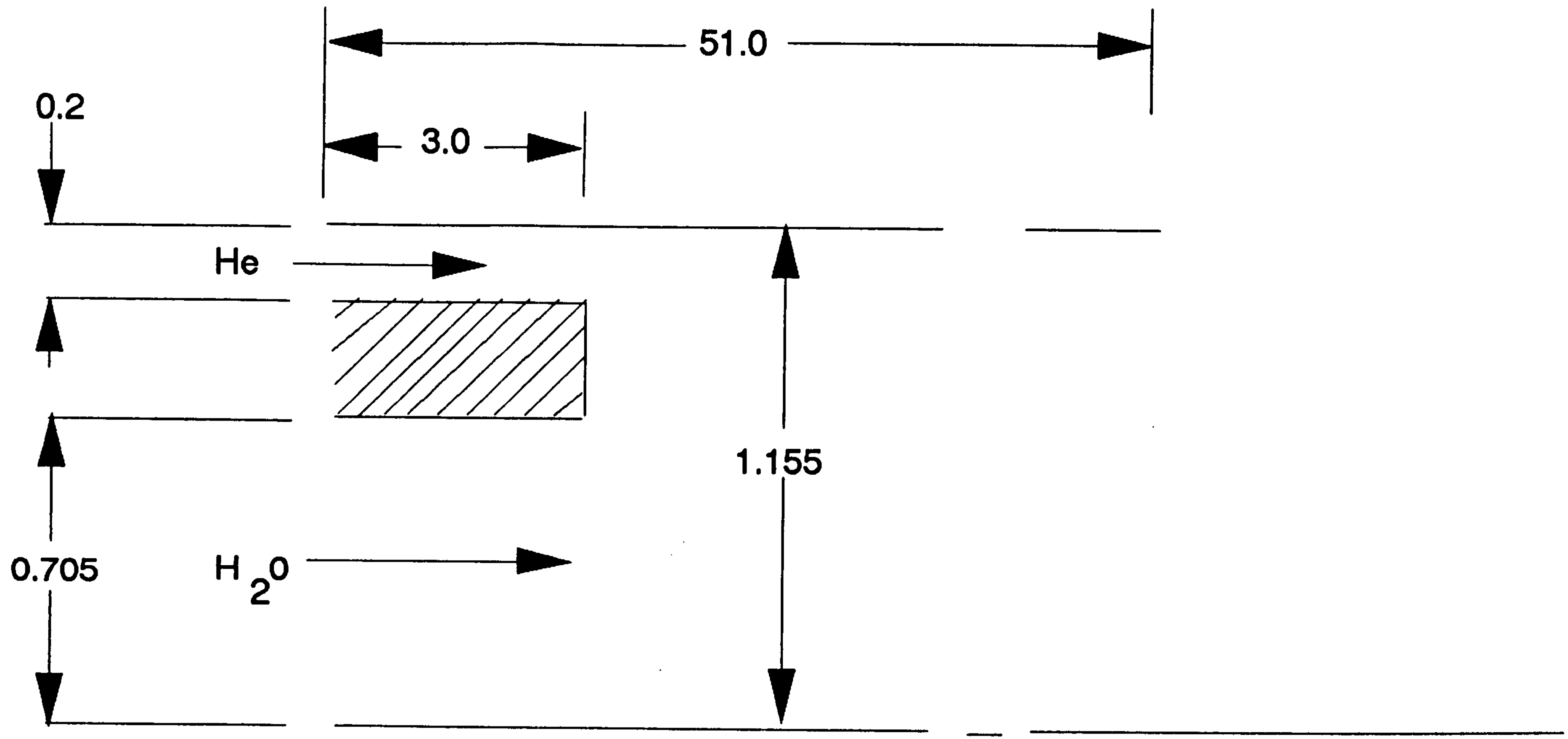


Figure 8. Three Concepts of Mixing Helium Gas With Lox/Hydrogen Combustion Products

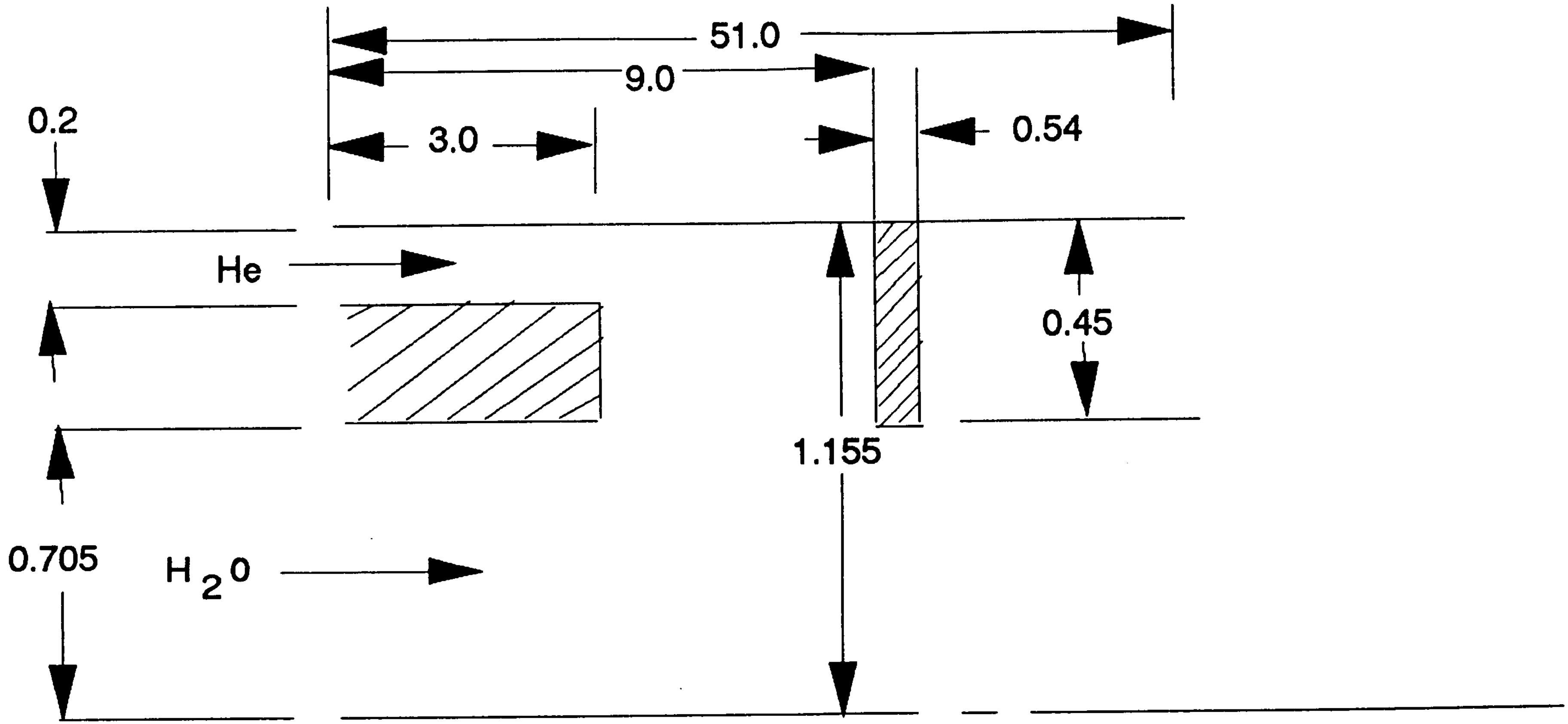


Helium inlet conditions:
- Velocity: 271 ft/s
- Temperature: 37° R
- Pressure: 2950 psia

Combustion product inlet conditions:
- Velocity: 957 ft/s
- Temperature 6808° R
- Pressure 2950 psia

DRAWING NOT TO SCALE

Figure 9. Geometry and Inlet Conditions Used in the Evaluation of the Coaxial Flow Concept



Helium inlet conditions:
- Velocity: 271 ft/s
- Temperature: 37° R
- Pressure: 2950 psia

Combustion product inlet conditions:
- Velocity: 957 ft/s
- Temperature: 6808° R
- Pressure: 2950 psia

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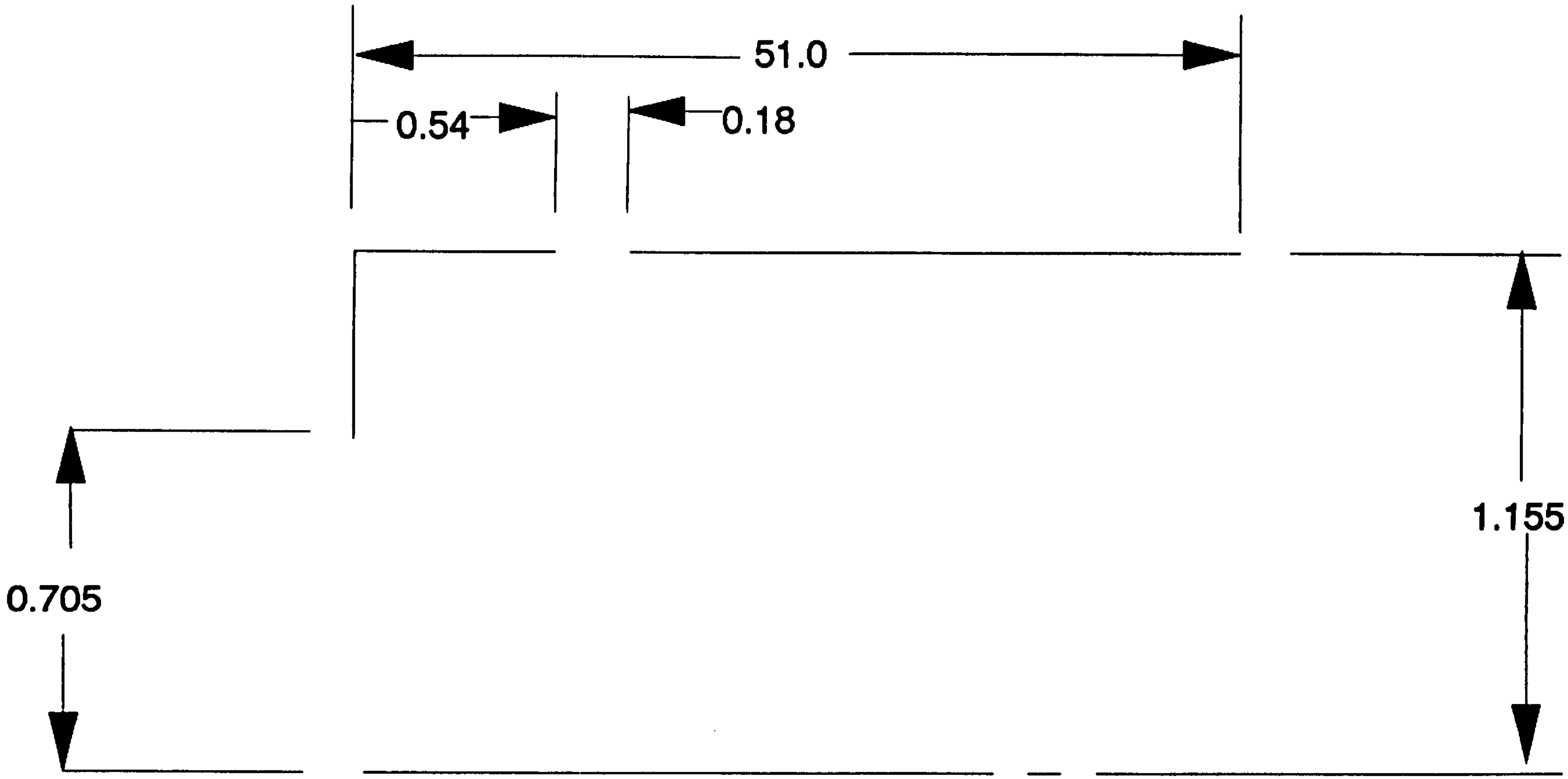
Figure 10. Geometry and Inlet Conditions Used in the Evaluation of the Coaxial Flow With Turbulence Ring Concept



Helium inlet conditions:

- Velocity: 271 ft/s
- Temperature: 37 $^{\circ}$R
- Pressure: 2950 psia

Combustion product inlet conditions:

- Velocity: 957 ft/s
- Temperature: 6808 $^{\circ}$R
- Pressure: 2950 psia

DRAWING NOT TO SCALE

Figure 11. Geometry and Inlet Conditions Used in the Evaluation of the Radial Injection Concept

The analysis was based on the ideal gas equation of the state and incompressible flow, i.e., the local density is calculated as:

$$\rho = \frac{P\,R}{M\,T}$$

where T is the local gas temperature, M is local mixture average molecular weight, R is the universal gas constant, and P is the "operating pressure." It should be noted that the pressure used in the density calculation is assumed to be constant. This assumption is valid in flows where variations in local pressure are small. Since the helium gas is injected at a very low temperature and a very high pressure, the ideal gas assumption is certainly questionable. At 2950 psia and 40°R, helium density is calculated using ideal gas equation of state to be approximately 29.7 lbm/ft^3 while the "real" density is approximately 12.0 lbm/ft^3. Again, this is assumed not to have an effect on the relative results between the three designs, although the flow rate of helium is approximately 2.5 times the actual flow rate.

Calculated temperature distributions inside the heater for the three cases: coaxial flow, coaxial flow with a turbulence ring, and radial injection, are shown in Figures 12 through 14, respectively. For all three cases, the temperatures are almost uniform at the exit of the heater indicating good mixing of the helium and combustion gases.

The radial injection case provides better mixing with a slightly higher pressure drop than the coaxial flow case. The coaxial flow with turbulence ring design provides the best mixing because the ring helps directing the flow of the helium gas into the combustion gas as shown in Figure 15. Furthermore, the ring generates more turbulence which enhances mixing of the gases in the downstream region. The evidence of more turbulence generation by the turbulence ring is seen by the differences in the turbulence kinetic energy profiles for cases with and without the ring as shown in Figures 16 to 18. Figure 16 shows that the maximum turbulence kinetic energy for the case without the ring is only 1.6E+05 ft^2/sec^2. Figure 17 shows that the maximum turbulence kinetic energy for the case with the ring is approximately 1.36E+06 ft^2/sec^2, almost an order of magnitude increase over the case without the ring. Figure 18 is a replot of Figure 17 but with a different contour scale (the maximum contour level was set to be equal to the maximum contour level used in Figure 16, i.e. 1.6E+05 ft^2/sec^2).

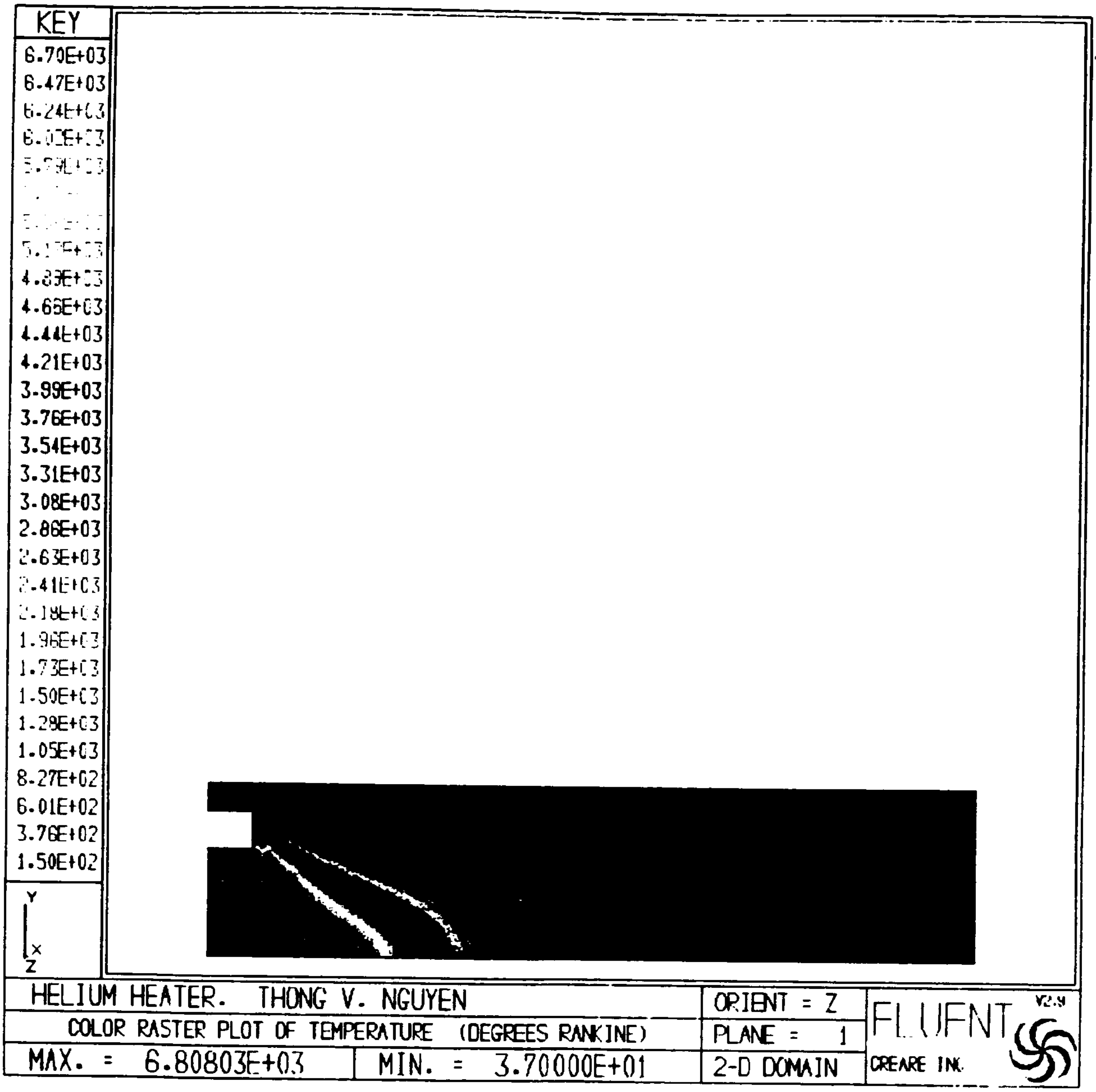


Figure 12. Temperature Distribution for the Coaxial Flow Case. (Note: Scale Expanded 10:1 Radially)

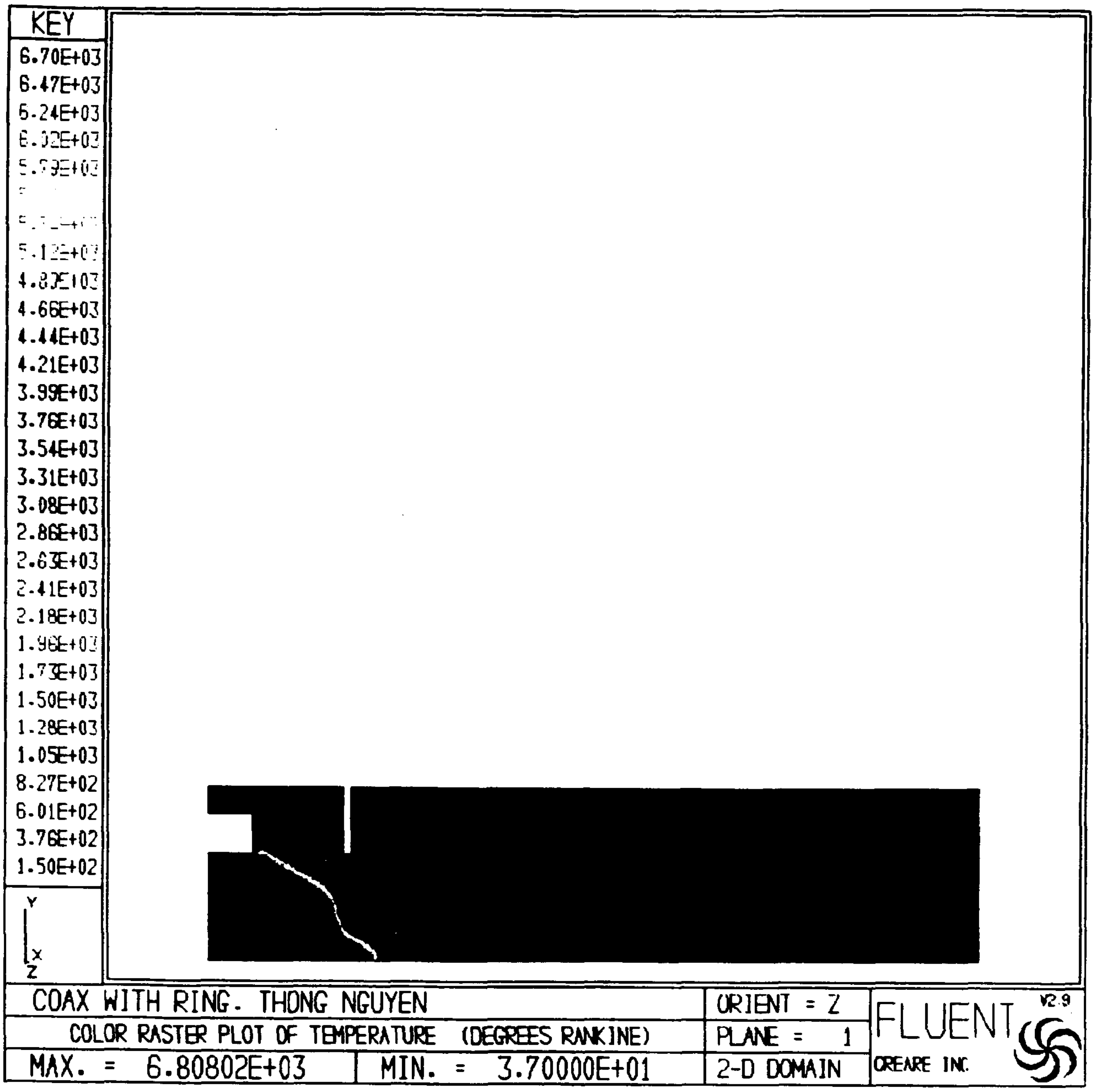


Figure 13. Temperature Distribution for the Coaxial Flow Case With a Turbulence Ring. (Note: Scale Expanded 10:1 Radially)

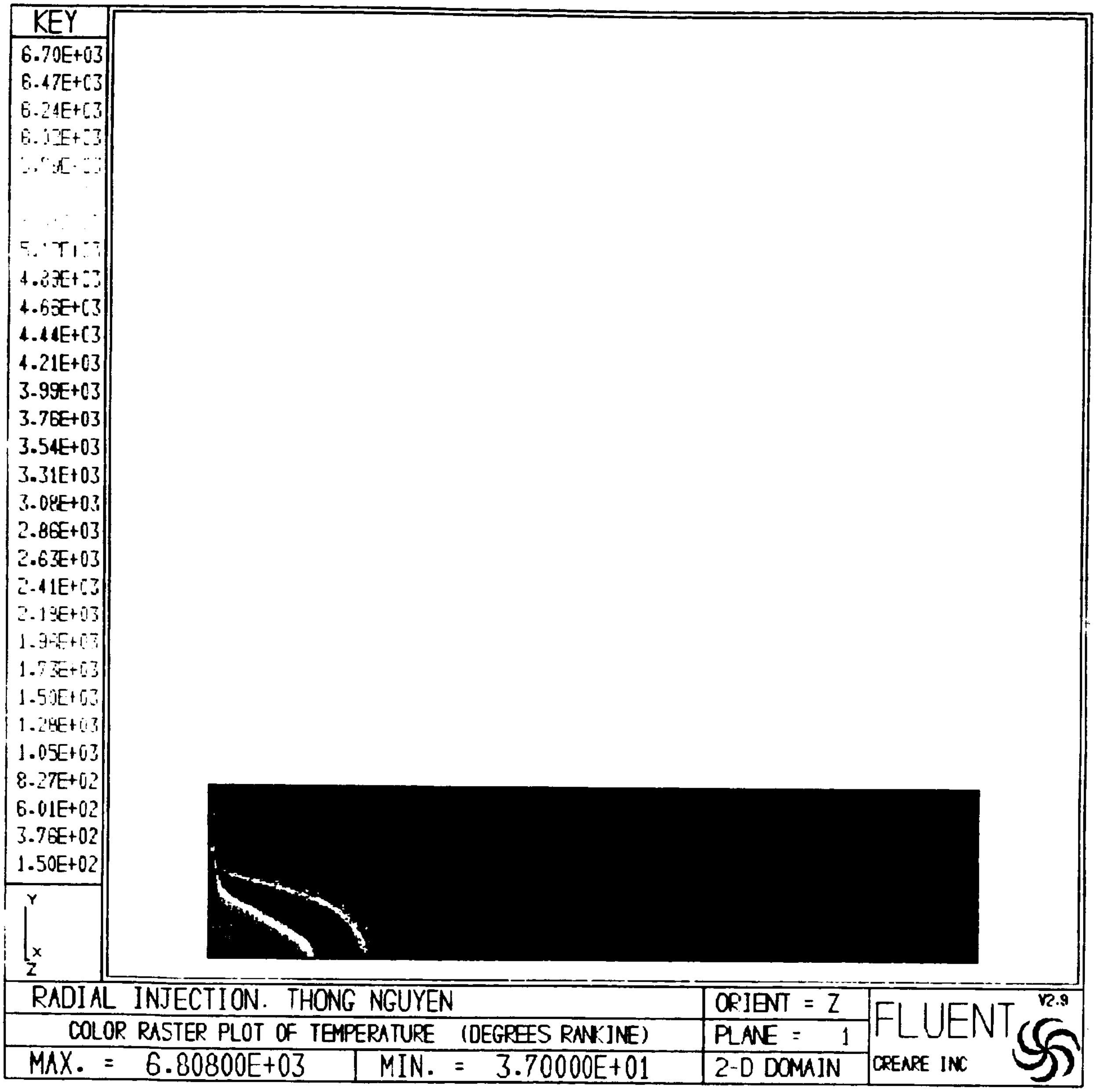


Figure 14. Temperature Distribution for the Radial Injection Case. (Note: Scale Expanded 10:1 Radially)

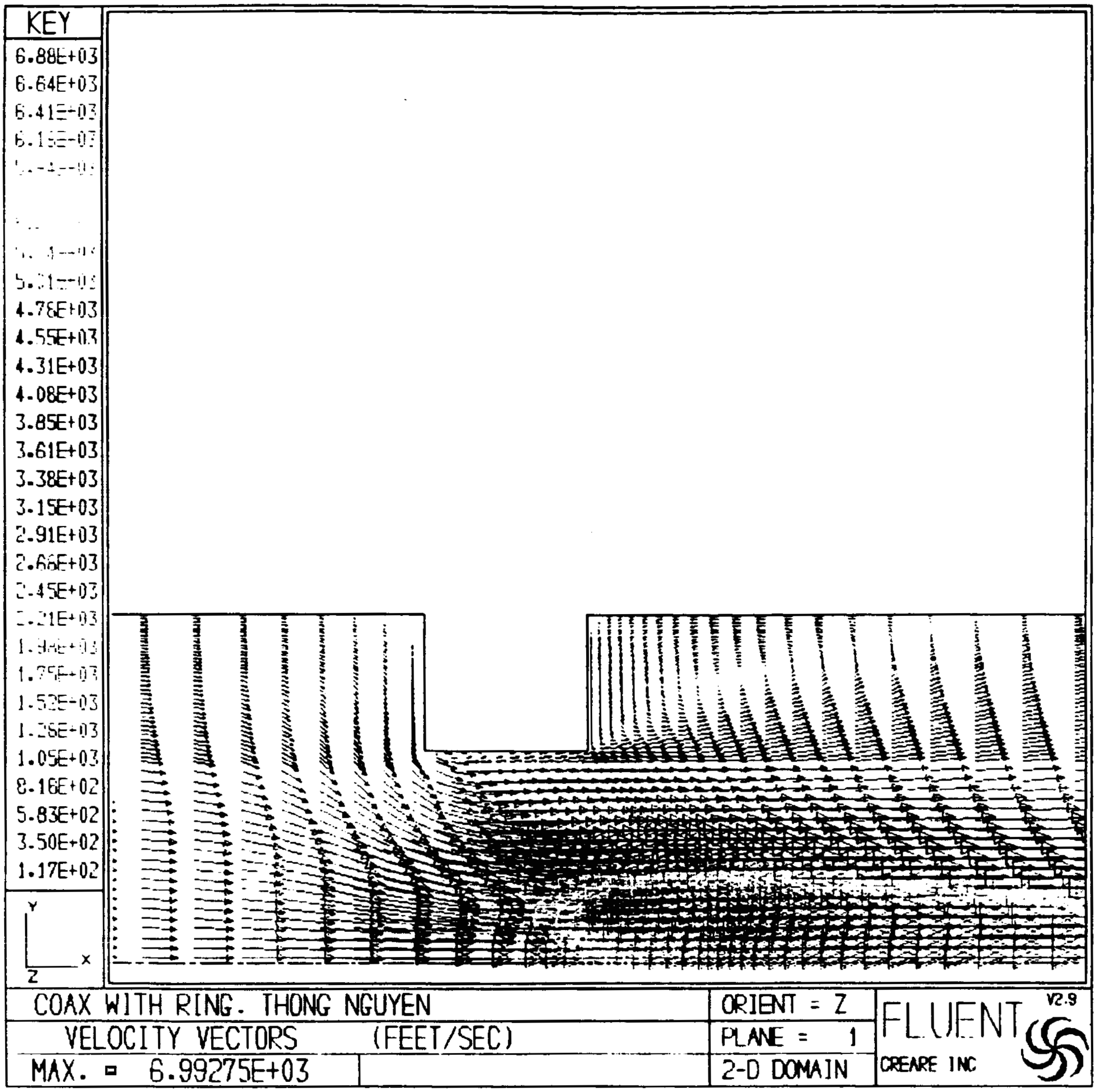


Figure 15. A Turbulence Ring Enhances Mixing By Directing the Flow of Helium Into the Combustion Gas

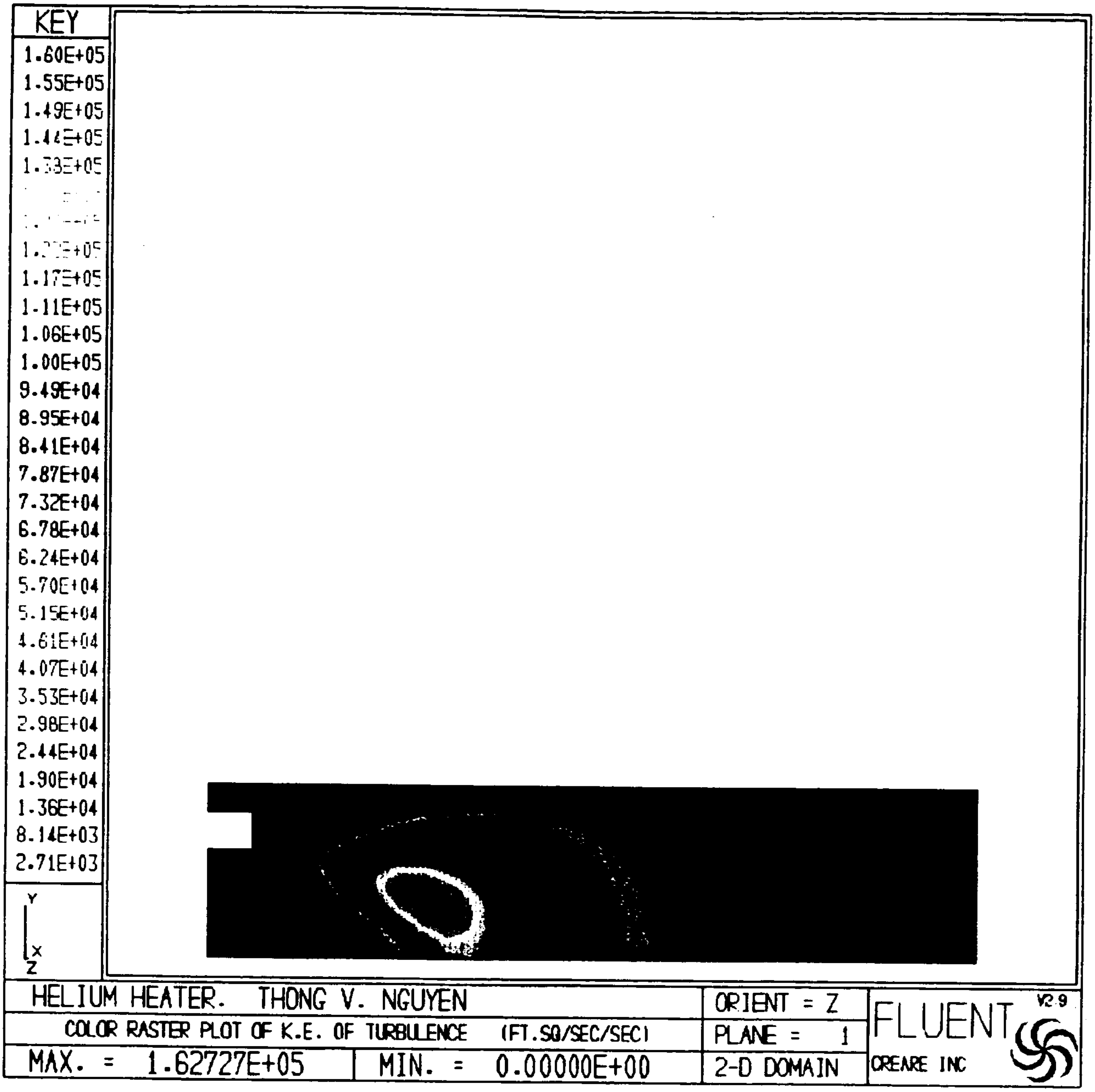


Figure 16. Turbulence Kinetic Energy Profile for the Coaxial Flow Without a Turbulence Ring

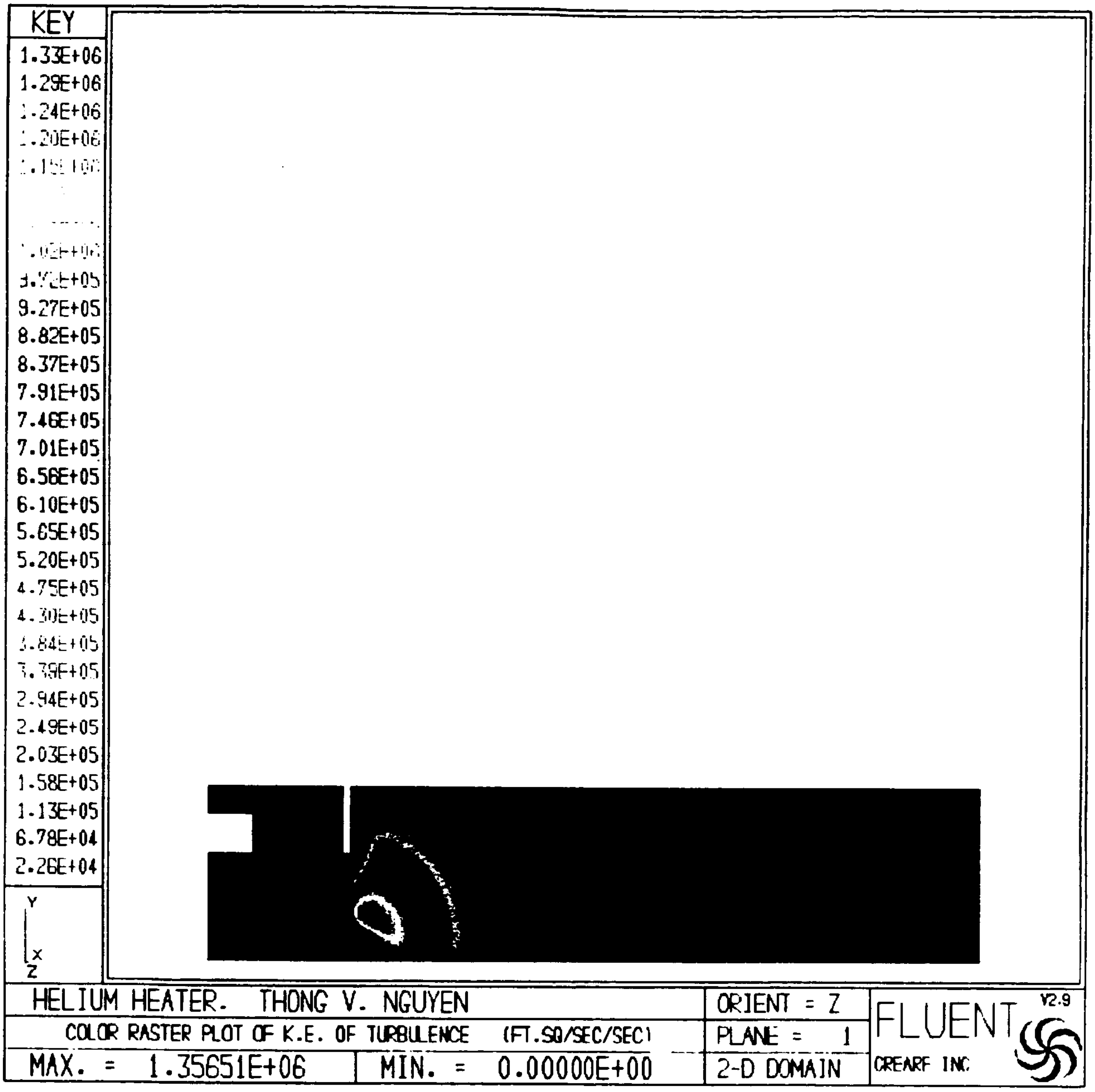


Figure 17. Turbulence Kinetic Energy Profile for the Coaxial Flow With a Turbulence Ring

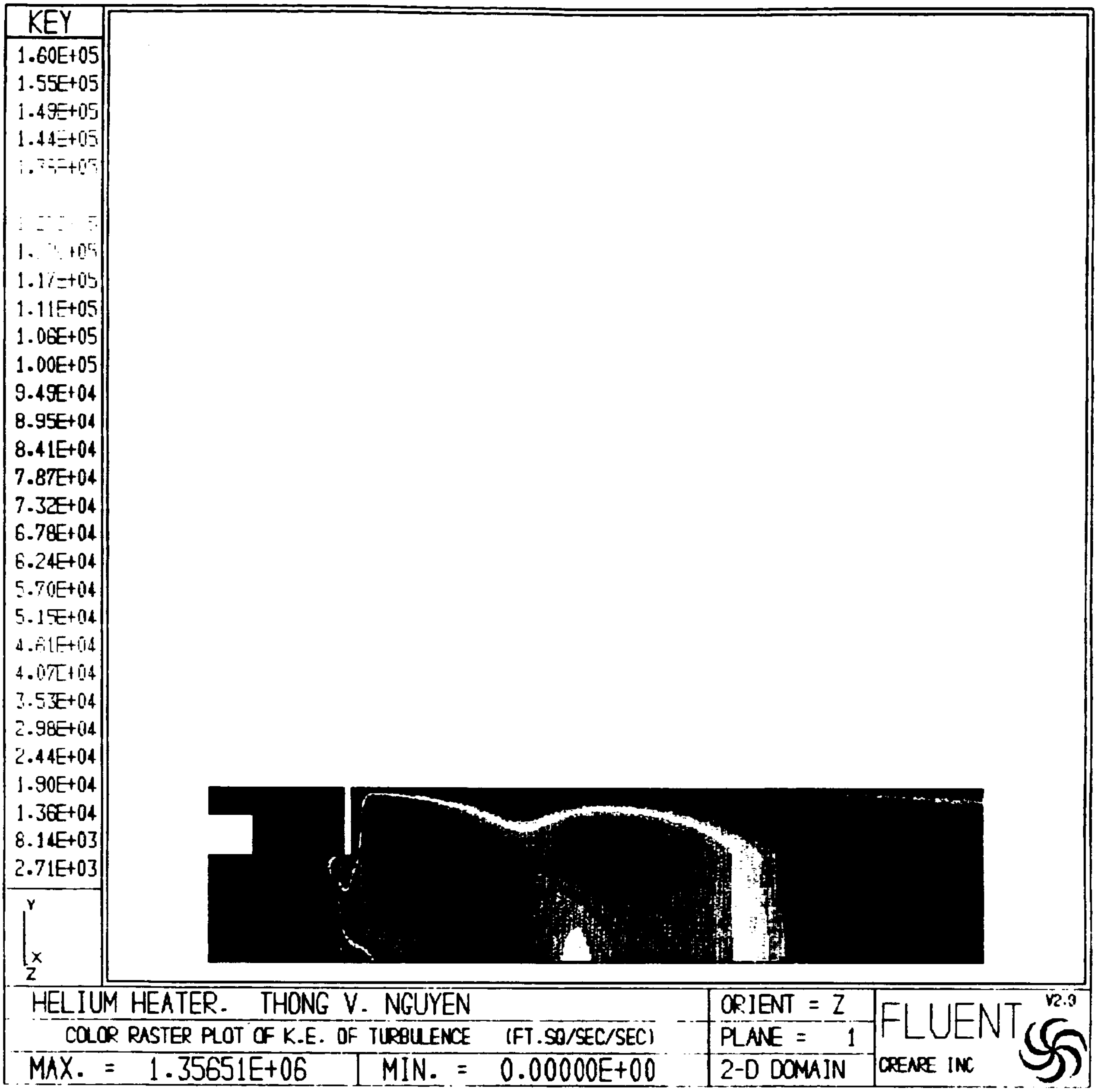
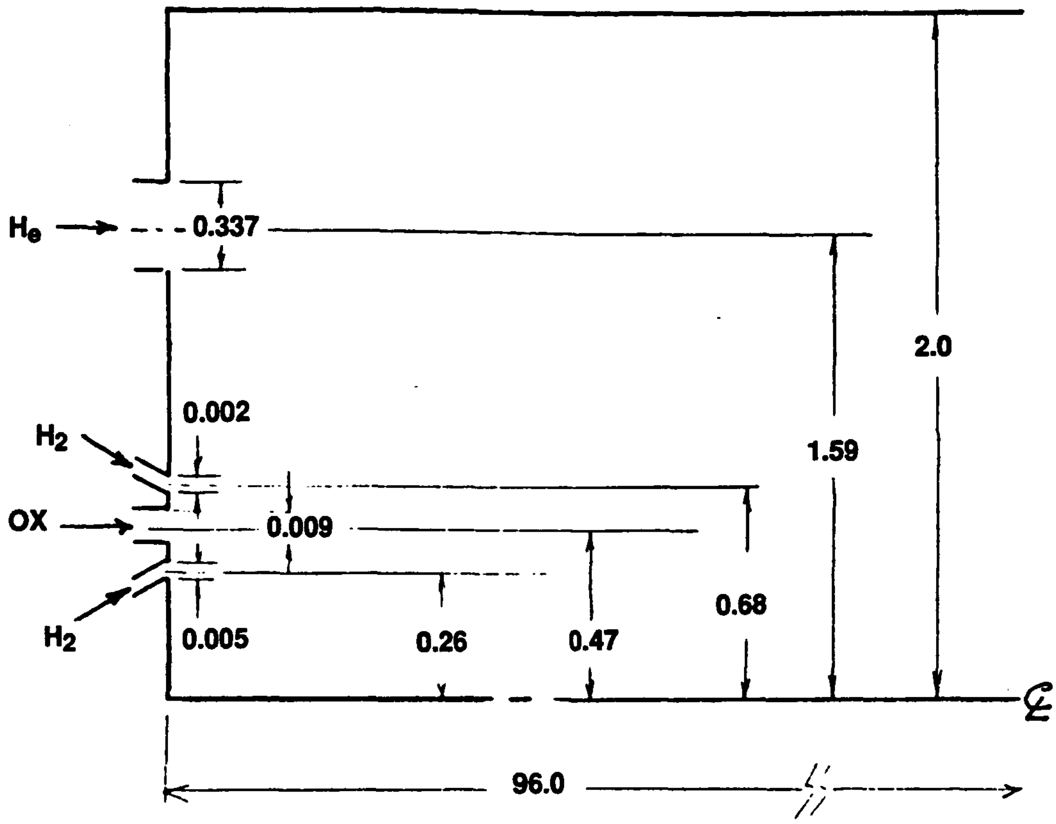


Figure 18. Turbulence Kinetic Energy Profile for the Coaxial Flow With aTurbulence Ring Case. (Note: Contour Scale is Set to be the Same as Figure 16)

Comparison between Figure 16 and Figure 18 clearly shows a much larger area of high turbulence intensity (greater than 1.6E+05 ft^2/sec^2) generated by the ring. This coaxial flow with turbulence ring design, however, has a significantly higher pressure drop than the other designs. The height of the ring step obviously has a strong effect on both mixing and pressure drop. Increased step height results in more mixing and also higher pressure drop. This design offers the flexibility of trading between pressure drop and the degree of mixing or mixer length. At zero height, the mixing and pressure drop will be identical to the case of coaxial flow. As the height is increased, more mixing is obtained but the pressure drop also increases. It is expected that at some step height, the design would give mixing and pressure drop results similar to those in the radial injection design. As a result, the radial injection design was recommended to be eliminated from further study because it is relatively more complex in design and offers no significant advantages over the coaxial flow with turbulence ring design.

A rigorous analysis using the improved version FLUENT 3.02 was initiated to calculate more accurately the pressure drop and the radial profiles of temperature and chemical species composition. The analysis accounts for the mixing and reaction of oxygen and hydrogen. The local thermodynamic properties of the mixture is calculated from the individual component species. The thermodynamic and transport properties of each component species as functions of pressure and temperature are calculated using the computer code MIPROPS (Ref. 4) and the computer code TRAN72 (Ref. 5). The computer code MIPROPS, developed by the National Bureau of Standard, is capable of calculating accurately the thermophysical properties from a very low (even at cryogenic) temperature up to some temperature limit, approximately few hundreds to a thousand degrees Rankine. In the higher temperature range, the computer code TRAN72 is used to calculate the properties assuming the gases obey the ideal gas law. This assumption is reasonable at high temperature.

The heater dimensions and the operating conditions used in the rigorous analysis are shown in Figure 19. The flow was assumed to be axisymmetric in the present analysis (although it is three-dimensional in reality). In consideration of computer time and program schedule and cost hydrogen and oxygen are injected into the heater through annular slots and are assumed to be in a gaseous state. The oxygen stream is parallel to the chamber axis with two hydrogen streams, one on the inside and another on the outside of the oxygen stream, directed toward the oxygen stream at an



Helium inlet conditions:

- o Velocity = 140 ft/s
- o Temperature = 37^{o}R

Oxygen inlet conditions:

- o Velocity = 40.8 ft/s
- o Temperature = 162^{o}R

Hydrogen inlet conditions:

- o Velocity = 1403 ft/s
- o Temperature = 40^{o}R
- o Impingement half angle = 30^{o}

Figure 19. Geometry and Inlet Conditions Used in the Reacting Flow Analysis

30 degree angle. A one-step reaction is assumed for the reaction of oxygen and hydrogen. It is intended to use the one-step reaction to obtain convergence on flow field solutions, then the analysis will be extended to multi-step reactions to calculate more accurately the chemical composition including intermediate species. This approach is expected to reduce CPU time substantially.

The analysis was not completed at the time of receipt of the stop work order. Intermediate calculated results are shown in Figures 20 to 22. Calculation residuals which measure the convergence of the solutions to the equations governing the flow are fairly large indicating that the current results are still far from the converged solutions. Figure 20 shows the temperature distribution in the heater. While a reasonable temperature distribution is seen in the upstream region near the inlet, the temperature distribution in the downstream region is not realistic as shown by some isolated local hot regions (difficult to be seen in the figure due to poor print resolution). This is typical in intermediate results where convergence has not been reached. Figure 21 shows a close-up plot of the temperature distribution near the injector face. Figure 22 shows the development of the flow near the inlet with recirculation flow patterns clearly indicated by the gas velocity vectors. Examining intermediate results reveals some mixing of the hydrogen with the helium, such mixing may have an adverse effect on the heater performance, i.e., lower combustion efficiency and higher temperature variation in the exit for a given length. It should be cautioned that the calculated results presented in this section are not from a converged solution. The results should be used or interpreted cautiously.

d. Conclusions and Recommendations

Several conclusions can be made with regard to the analysis and the calculated results:

1. The computer code FLUENT is a powerful tool for analyzing reacting flows. It is suitable and very useful in the design and the analysis of the primary helium heater. It is recommended, however, to verify the code prediction validity using experimental data for similar flows. Several existing experimental data have been identified including those from the hydrogen/air mixing (reacting and non-reacting) study at AEDC (Ref. 6), hydrogen/air turbulence diffusion flame study at the

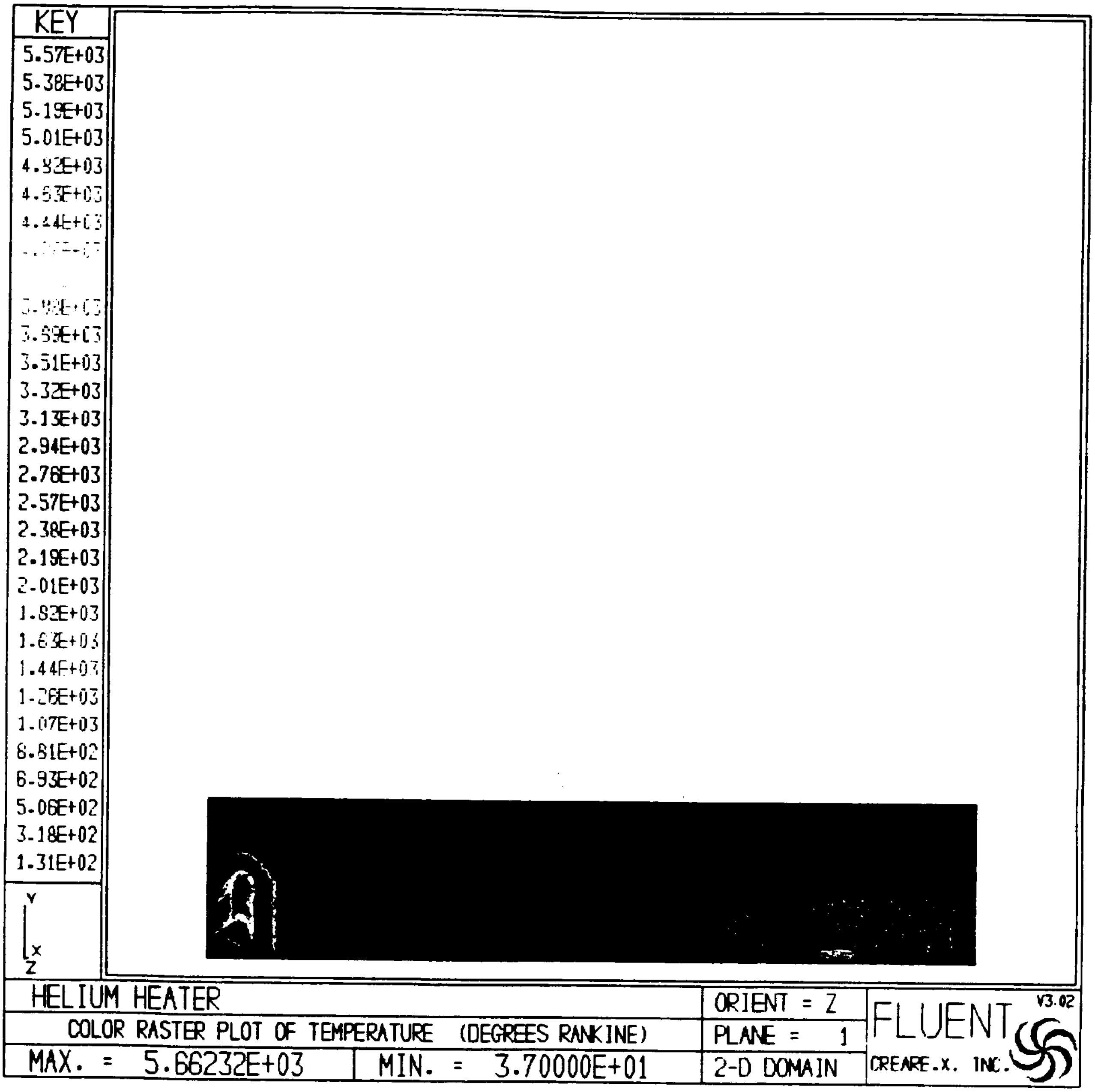


Figure 20. Temperature Distribution in the Heater (Note: Intermediate Results, Scale. Expanded 10:1 Radially)

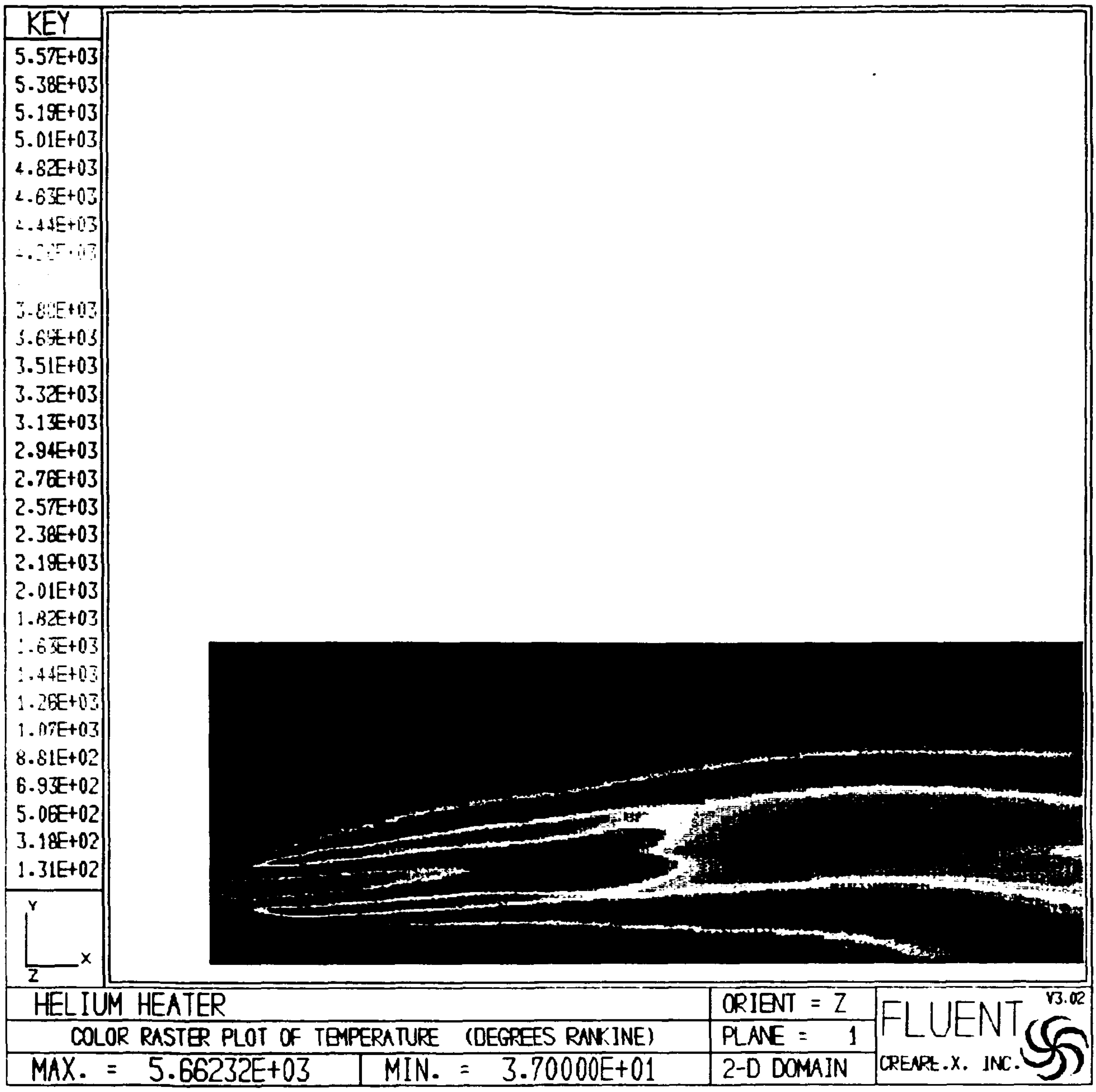


Figure 21. Temperature Distribution Near the Injector Face. (Note: Intermediate Results)

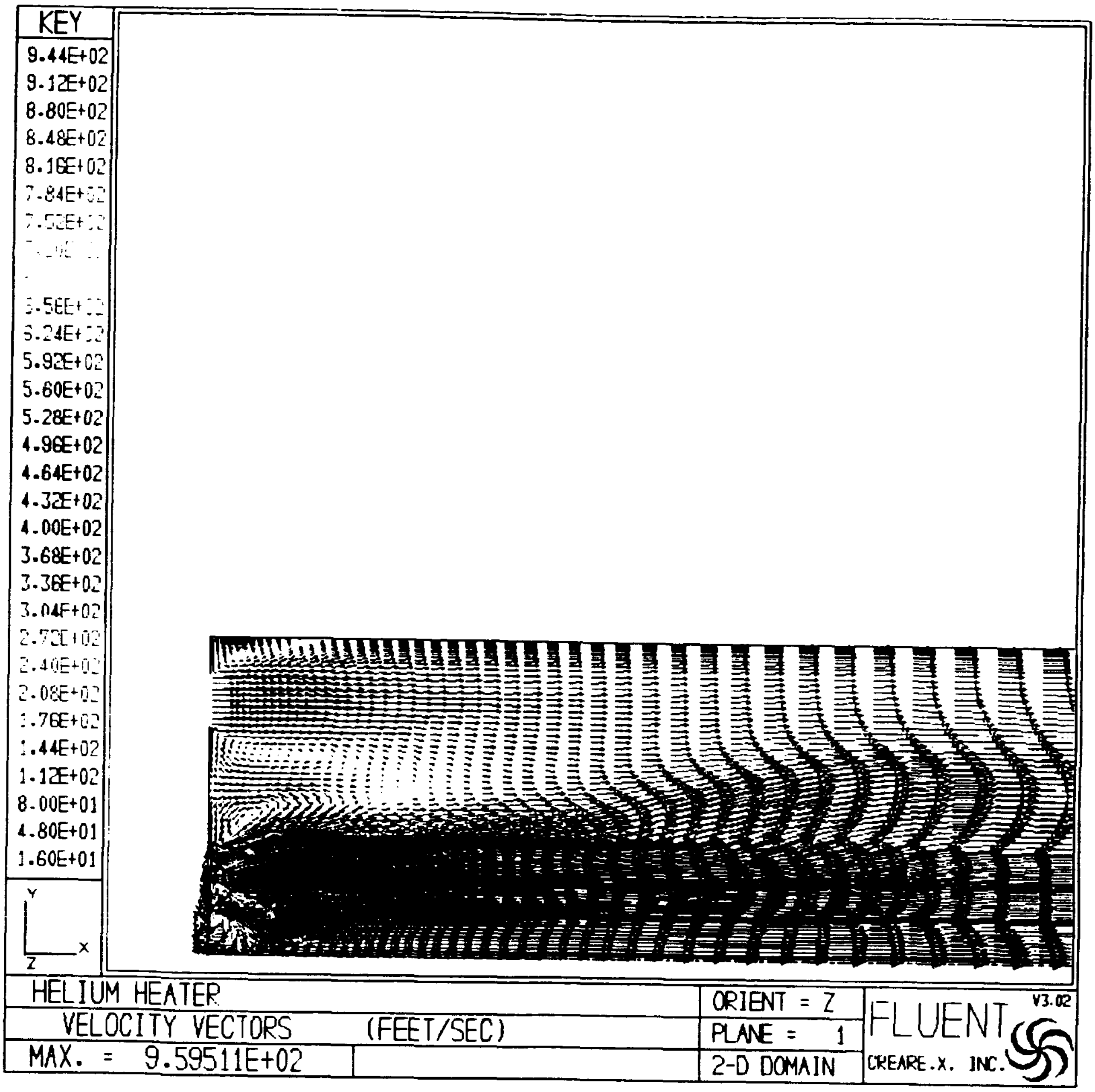


Figure 22. Velocity Vectors Near the Injector Face. (Note: Intermediate Results)

University of Sidney (Ref. 7), and hydrogen/argon/air turbulence diffusion flames study at the Combustion Research Facility of Sandia Laboratories (Ref. 8).

2. After validation, the code would be extremely helpful to the designer because 1) it can be used to determine whether a design satisfies the design requirements before actual hardware is built and tested; 2) it can provide information to guide development of alternative designs if the current design does not meet the requirement or if improvement of the heater performance (higher combustion efficiency, better mixing, and/or lower pressure drop) is desired.

3. Simplified analysis (non-reacting, ideal gas assumption) allowed the down selection of the mixing concepts to be made early, thus reducing detail design and analysis efforts.

4. The radial injection concept is recommended to be eliminated from further study because it is a relatively more complex design and the analysis shows that it does not offer significant advantages over other mixing concepts.

5. Turbulence ring enhances the mixing process but causes a higher pressure drop.

6. Mixing of the helium with one of the reactants before complete combustion of hydrogen and oxygen may not only adversely affect the combustion efficiency but also increase temperature variations at the exit for a given heater length. Further investigation of this area is recommended for technology development.

2. Thermal Analysis

A thermal analysis was conducted for the injector face and the chamber/mixing device. It was desired to know whether a conventional monoplate injector design was thermally adequate or if a "cooled" injector was necessary for face compatibility. Secondly, three mixing devices were chosen as design concepts. The simplest mixing device consists of injecting all of the helium axially around the outer circumference of the injector like a film coolant. Mixing of the helium and the combustion products would occur through turbulent shear mixing and diffusion. Mixing could be enhanced by placing a trip ring a certain distance downstream of the injector face.

Another method of mixing would be to inject most of the helium radially into the mixer some specified distance from the injector face. The section of the chamber upstream of the radial injection holes would require film cooling. The length of this section would depend on the distance required to achieve an acceptable combustion efficiency.

a. Chamber Film Cooling Analysis

A study of the amount of helium required to thermally protect the LOX/LH_2 combustion chamber without any other cooling was made. Such "film cooling" could be used for the radial injection design or to cool the combustion isolation sleeve if desired. A parametric study was conducted to determine the minimum helium film coolant flowrate required for chamber L/D's ranging from 1 to 4.

Table III is a summary of the operating conditions used for this analysis. The table shows the operating conditions for normal operation (2 HEATERS) and for a heater out condition (1 HEATER).

The helium is being supplied by a tank that has a secondary heater in it. During a typical engine firing the helium will initially be at high pressure, low temperature, and high flowrate, but by the end of the mission the pressure will have dropped slightly and will be flowing at a much lower mass flowrate and higher temperature. The maximum helium injection velocities listed in Table III are based on the maximum available pressure drop between the helium tanks and the helium heater for the given operating condition.

The entrainment film cooling model was used to evaluate the helium film cooling requirements for the design where there is normal injection downstream of the injector (see Figure 23). The maximum allowable adiabatic wall temperature was chosen to be 1000°F. TRAN72 (Ref. 5) was used to parametrically determine the helium concentration required to have an adiabatic wall temperature of 1000°F. Concentration is defined as the mass fraction of the coolant within the gas mixture near the wall. In the case of inert film cooling the concentration is equal to the film cooling effectiveness. Figure 24 shows the results of this parametric study. The required concentration is .737 and .776 at the start and just before duty cycle completion, respectively. The concentration will transition between these values during the firing.

TABLE III
Thermal Analysis Design Parameters

FOUR DESIGN POINTS:

	1HEATER		2HEATERS	
FLOW	MAX	MIN	MAX	MIN
PRESSURE	1530.	1490.	1530.	1460.
HELIUM MASS FLOWRATE	30.	22.8	15.	11.4
CORE MASS FLOWRATE (GG)	7.57	4.2	3.875	2.1
TEMP. OF HE (IN TANK), R	37.	300.	37.	300.

o MAXIMUM HELIUM INJECTION VELOCITY (FT/SEC)

	VINJ.
MAX PC, 1 HEATER	165.9
MIN PC, 1 HEATER	357.0
MAX PC, 2 HEATERS	165.9
MIN PC, 2 HEATERS	357.0

o MAXIMUM ALLOWABLE GAS SIDE WALL TEMPERATURE IS 1000 F o DETERMINE MINIMUM FILM COOLING REQUIRED FOR L/D = 1,2,3,4

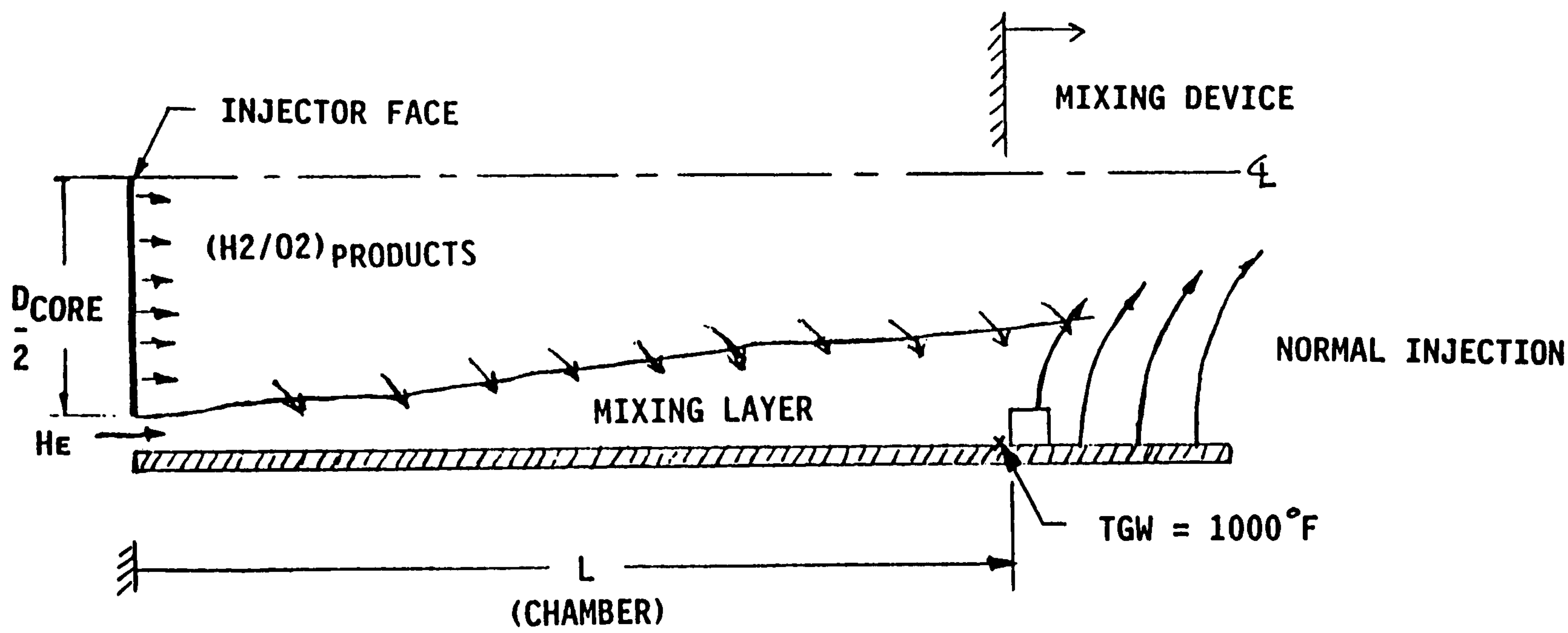


Figure 23. Entrainment Film Cooling Model Used Upstream of the Mixing Device

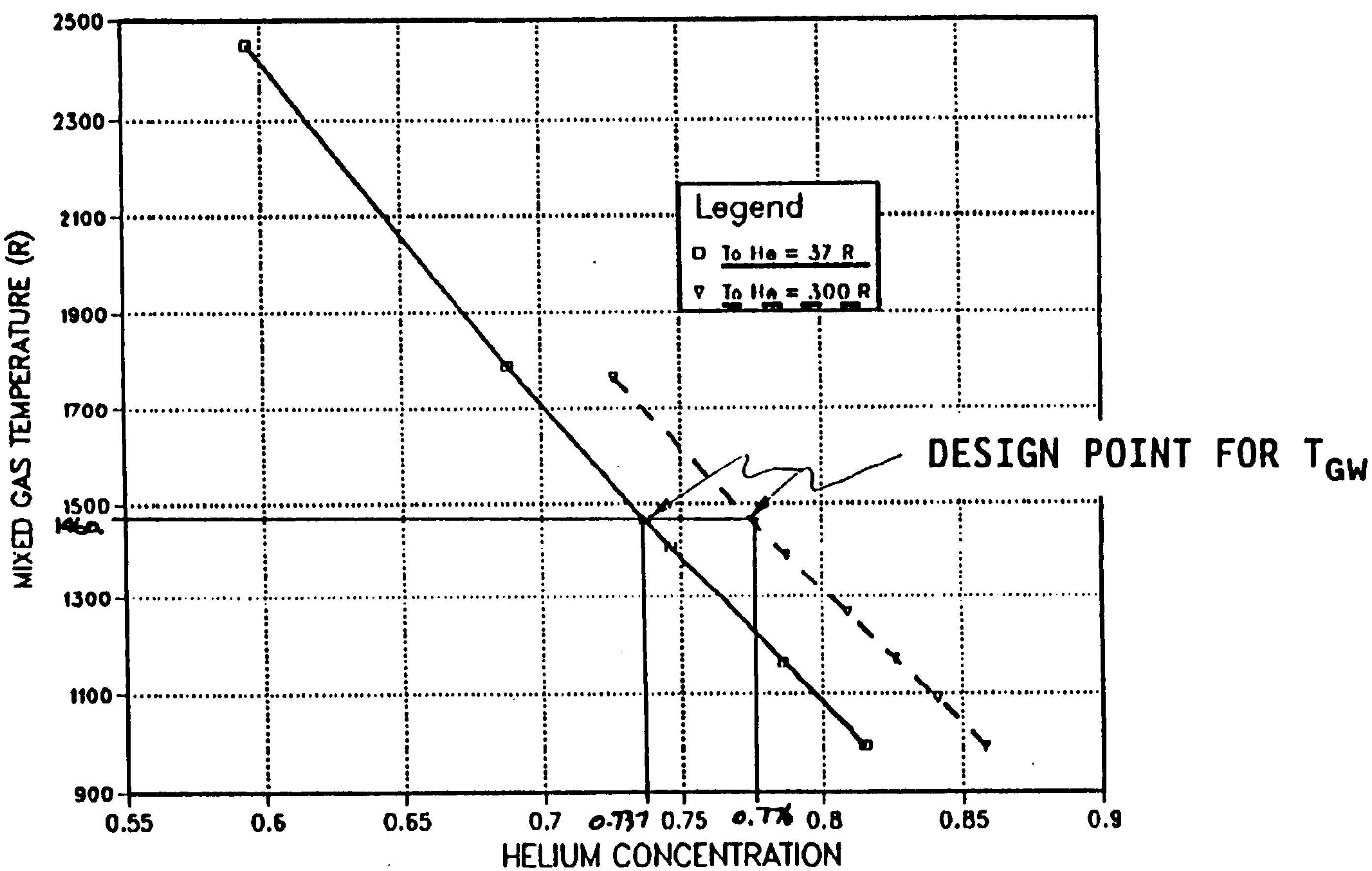


Figure 24. Helium Concentration of Near .75 is Required to Maintain a 1000°F Mixed Gas Temperature

The key correlating parameter used in film cooling analyses is the entrainment fraction. An injection point entrainment fraction was calculated as a function of coolant injection velocity ratio, density ratio, and coolant injection Reynolds number. It was derived from laboratory gas film cooling effectiveness data for plane, unaccelerated flow (Ref. 9). These data were obtained using air, helium, argon, and Arcton 12 as the film coolants, with air as the mainstream flow in each case. A multiplier (obtained from Ref. 10) was also included to account for combustion effects. This multiplier varies with axial distance. It should be noted that this test data is based on ambient temperature helium film cooling injection. This design uses cryogenic helium film cooling injection. Table IV describes the correlation used and the asymptotic multipliers also.

Figure 25 is a plot of the minimum helium mass flowrate required for L/D's ranging from 1 to 4 for all four operating conditions. The max Pc (initial time)-1 HEATER case requires the most coolant because it has the highest LH_2/LO_2 mass flowrate, and hence, highest heat output. The diameter of the "pure combustor" section is 2.2 inches. The results show that the highest helium mass flowrate that could be required would be a 1.7 lbm/sec for a chamber L/D equal to 4. The helium mass flowrate required during normal operation would vary between .94 lbm/sec and .51 lbm/sec for L/D equal to 4. These results indicate that less than 7% of the total helium flow is required to film cool the chamber to an L/D of 4:1.

Table V lists the significant film cooling parameters resulting from the parametric study. The case of min Pc-1 heater always gave the highest helium injection velocity. Therefore, this condition was analyzed first. The required slot height was calculated for a given L/D and the other three operating points were analyzed with that slot height and L/D.

Only the conditions of min Pc resulted in velocity ratios that were within the range of the data base for helium film cooling. The data base had velocity ratios of .8 and 1.0. This analysis predicts velocity ratios of .8 and .88. The max Pc cases resulted in velocity ratios of .22 and .24, which are well outside the range of the test data. Reference 10 did test hydrogen film cooling with a H_2/O_2 core mixture ratio of 2.0 and a velocity ratio of .25. This data is most likely not applicable because core mixture ratio has a strong effect on the entrainment fraction. Also, the cases of L/D equal

TABLE IV
Resulting Film Cooling Parameters

0 ENTRAINMENT FRACTION, $K = K_O \, (K/K_O)$

A. INJECTION POINT ENTRAINMENT FRACTION, KO CALCULATED FROM:

$$K_O = \frac{0.1\,(U_C/U_E)}{\left(\frac{C}{E}\right)^{0.15} \left(\frac{U_C}{U_E}\right) Re_C^{0.25}}$$

B. ENTRAINMENT FRACTION MULTIPLIERS:

FOR $L/D = 1$, $K/K_O = 2.5$
FOR $L/D = 2, 3, 4$, $K/K_O = 2.12$

0 DATA FROM COMBUSTION EFFECTS ON FILM COOLING PROGRAM

TEST #120 HE FILM COOLING
$MR_{GG} = 7.46$, $U_C/U_E = .82$, $L/D = 1.0$ FOR K/K_O
$SH = .059$ IN., $T_{LIP} = .020$ IN.

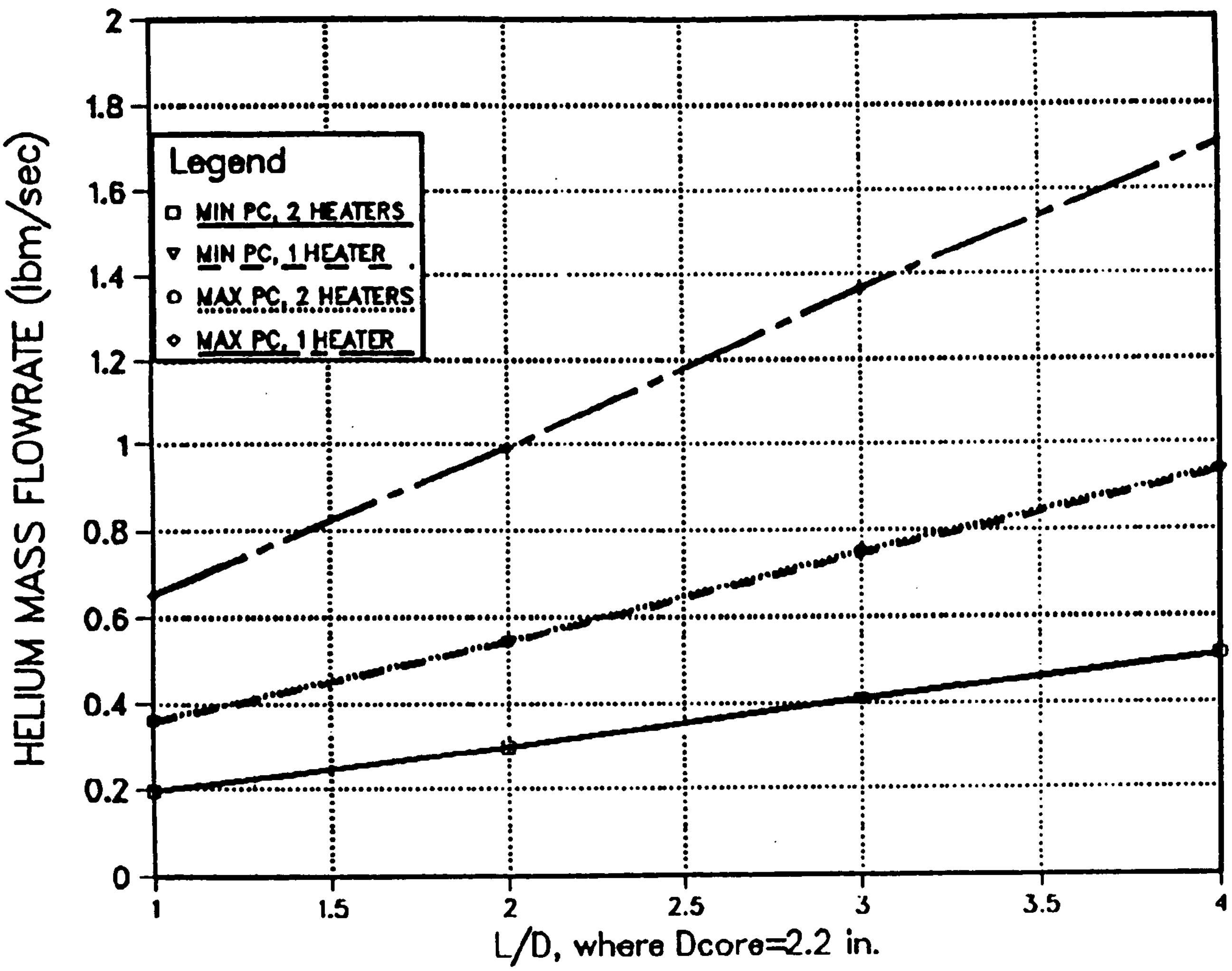


Figure 25. Minimum Helium Mass Flowrate Required for a Maximum Gas Side Wall Temperature of 1000°F

TABLE V
Significant Parameters From the Film Cooling Analysis

			L/D			
FLOW	NO. HTR		1	2	3	4
MIN	1	VINJ. (FT/SEC)	357	357	357	357
		SH (IN.)	.012	.018	.025	.031
		UC/UE	.8	.8	.8	.8
		ENTRAINMENT FRACTION	.012	.009	.008	.008
MIN	2	VINJ. (FT/SEC)	198	199	197	198
		SH (IN.)	.012	.018	.025	.031
		UC/UE	.88	.89	.88	.89
		ENTRAINMENT FRACTION	.013	.010	.009	.009
MAX	1	VINJ. (FT/SEC)	93	94	93	94
		SH (IN.)	.012	.018	.025	.031
		UC/UE	.22	.22	.22	.22
		ENTRAINMENT FRACTION	.015	.011	.010	.010
MAX	2	VINJ. (FT/SEC)	52	52	51	51
		SH (IN.)	.012	.018	.025	.031
		UC/UE	.24	.24	.24	.24
		ENTRAINMENT FRACTION	.016	.012	.011	.011

to 1 and 2 are showing cooling injection slot height (gap across the annulus) to be too small for practical machinability.

The entrainment fractions used in this analysis were taken directly from the test data in Reference 10. It has been noted that a conservatism be added to these values when analyzing a final design.

b. Injector Face Thermal Analysis

A 10 quadlet element monoplate injector with ring manifolds was evaluated from a face cooling standpoint. Because the element density was so low there was a concern as to whether the face needed additional cooling or not. The present design has a .2 inch thick zirconium copper faceplate with a CRES injector core. The faceplate is heated on the front face by combustion products. The heat is absorbed by the propellants as they flow through the orifices and the distribution rings behind the faceplate. A 3-D P/THERMAL model was constructed to predict the temperature distribution in the faceplate.

At this point we are not able to predict the mixture ratio distribution across the injector face. Therefore, for conservatism, the mixture ratio that results in the highest gas side heat flux was used. It was parametrically determined that a mixture ratio of 5.5 would give the highest gas side heat flux. This is based on a non-reactive model using the BARTZ equation to calculate the heat transfer coefficient. Cg was assumed to be 1.0.

The Hess and Kunz correlation was used to calculate the coolant side heat transfer coefficient in the hydrogen channels and the Rousar-Spencer supercritical LOX correlation was used in the other channels. Enhancement factors were applied to the heat transfer coefficients in the orifices due to a sudden contraction. Figure 26 is a plot of the enhancement factor as a function of entrance length for both orifices derived from Figure 13-10 in Ref. 11. The LOX orifice diameter used in this analysis was .050 inch in diameter and the LH_2 orifice diameter was .035 inch.

The distribution ring geometry had not been defined up to this point. Therefore, the channel depth was assumed to be equal to the land width in the model geometry. The maximum allowable propellant velocity in the distribution

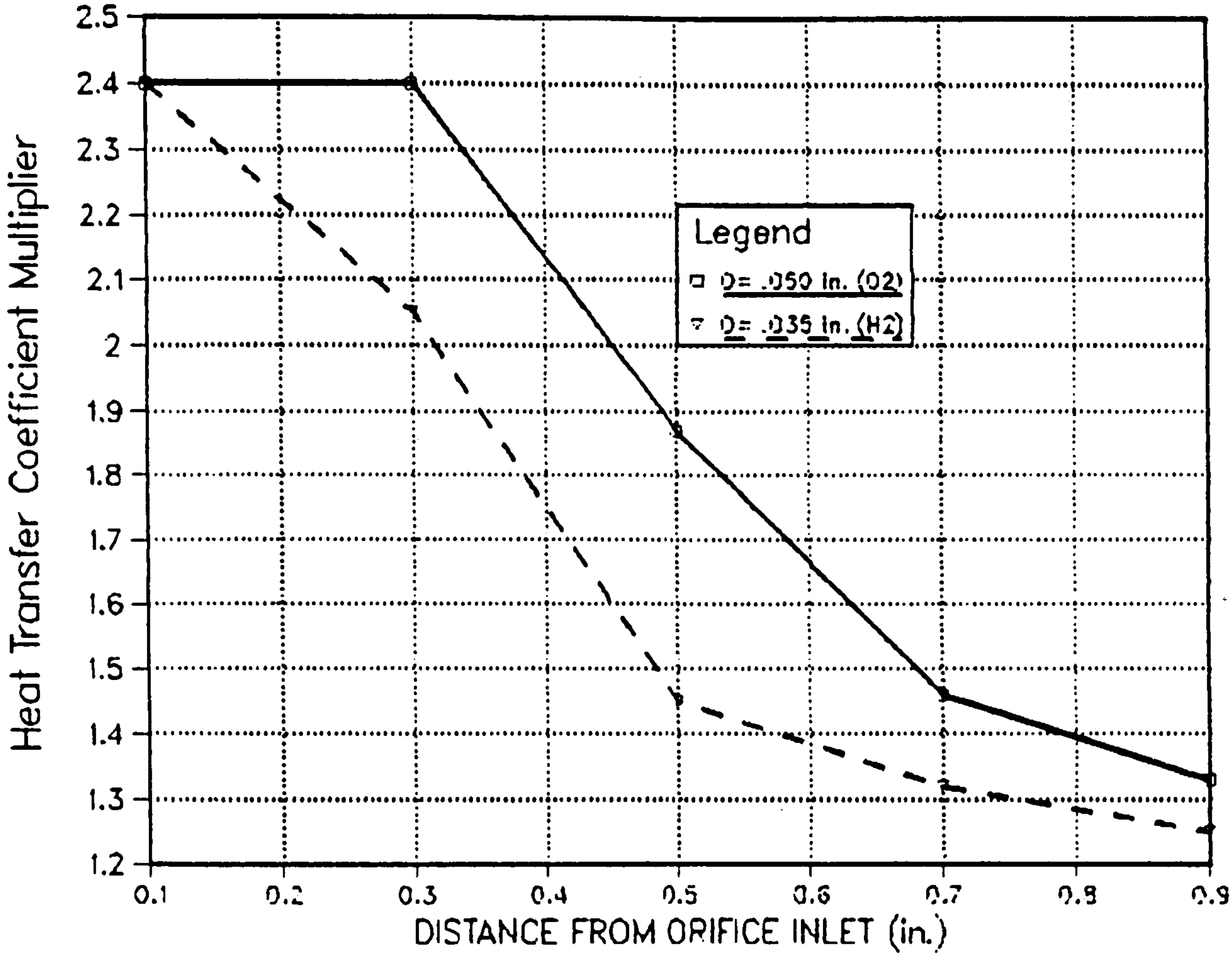


Figure 26. Injection Orifice Heat Transfer Coefficient Enhancement Factors (.2 Inch Thick Faceplate)

ring was assumed to be 20 percent of the injection velocity. The maximum injection velocity for the LOX is set at 107 ft/sec. The maximum injection velocity of the LH_2 is 416 ft/sec. A conservative enhancement factor of 2.0 was applied in the distribution rings due to flow downstream of a tee (see Refs. 12 and 13).

The monoplate with a distribution ring allows for two types of cooling mechanisms to exist. The heat can be absorbed by the orifices and the backside of the face plate. Either of the two can predominate depending upon the faceplate thickness. If the faceplate is thin the backside cooling will predominate because the coolant area of the orifices will be small. A thick faceplate will have a larger thermal resistance. The orifices will have a larger coolant area and, hence, absorb most of the heat.

A parametric study was conducted to determine the effect that faceplate thickness has on injector face surface temperature. A steady state analysis was run for faceplate thicknesses of .05, .1, .2, .4, .5, .8 inch using a P/THERMAL model of an outer quadlet element. Figure 27 is a plot of the steady state temperature distribution for a .2 inch thick faceplate. The maximum surface temperature is predicted to be 582°F, which is well below the maximum allowable surface temperature of 1000°F. A second, more complex, model was created in the core region to determine if the maximum surface temperature is higher in this region. The results (shown in Figure 28) suggest that the maximum surface temperature around the core elements is the same as the outer periphery elements. Figure 29 shows the maximum gas side surface temperature of the outer periphery for various faceplate thicknesses. The results show that the optimum faceplate thickness is .4 inch, which corresponds to 80 percent of the heat being absorbed by the injection orifices.

3. Combustion Analysis

An analysis was performed to determine the LOX and LH_2 flowrates required to meet the Table I design requirements. Existing design criteria and existing analysis models were also applied to define injection pressure drop requirements and essential chamber and injector design features. Details of these analysis results are provided in this section.

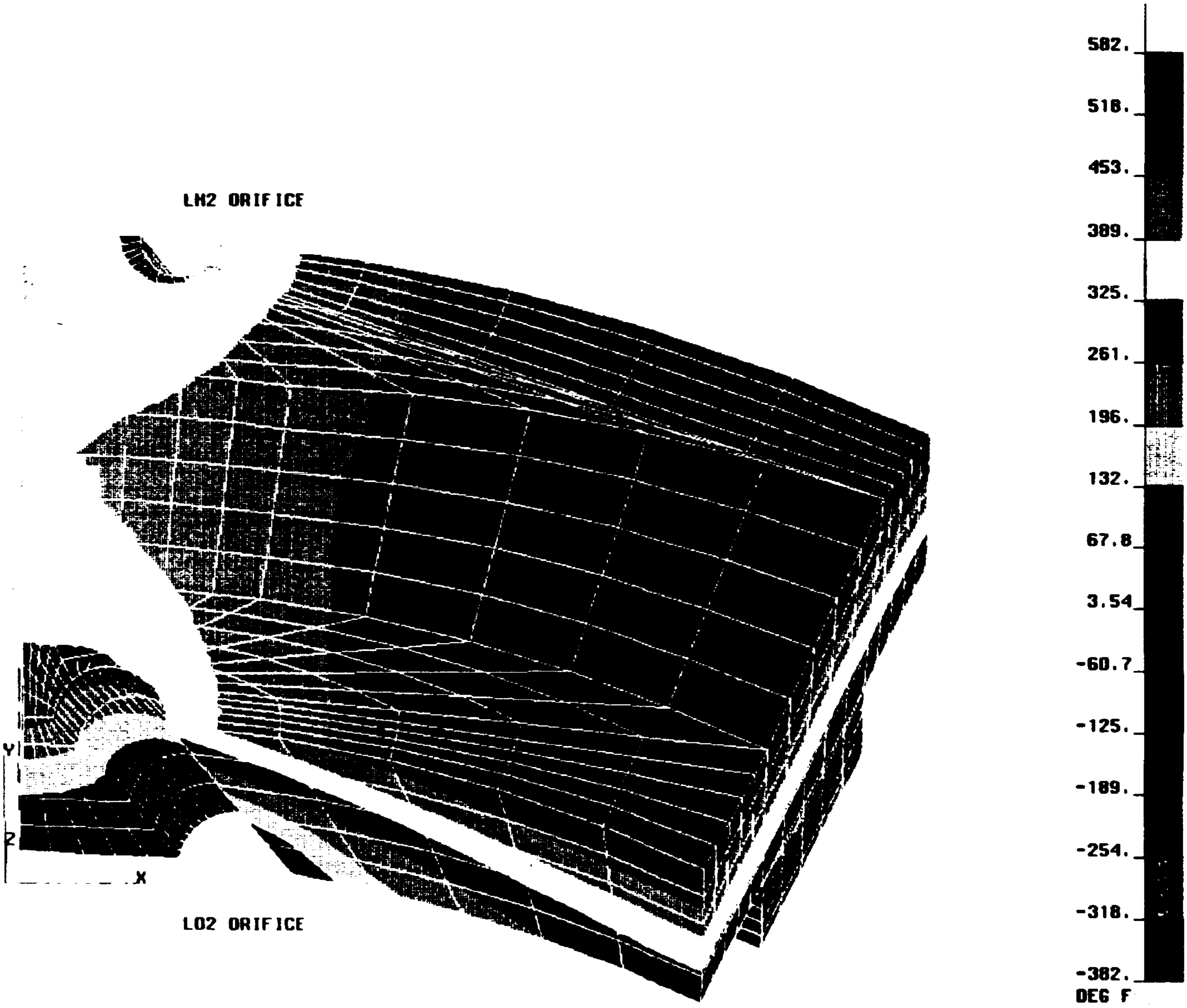


Figure 27. Steady State Temperature Profile for Outer Periphery Elements With a 0.2 in. Zirconium Copper Faceplate

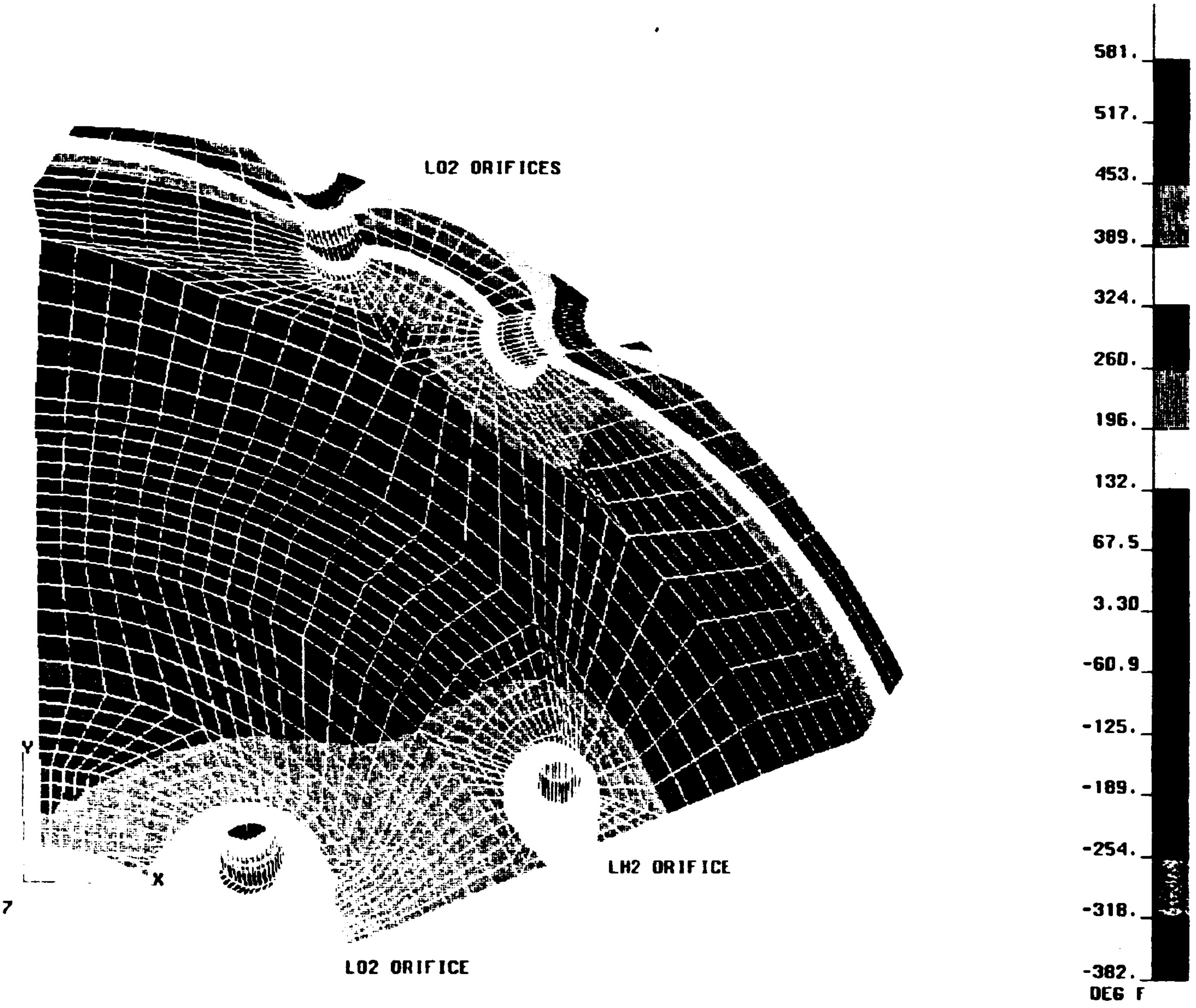


Figure 28. Steady State Temperature Profile for Inner Row Elements With a 0.2 in. Zirconium Copper Faceplate

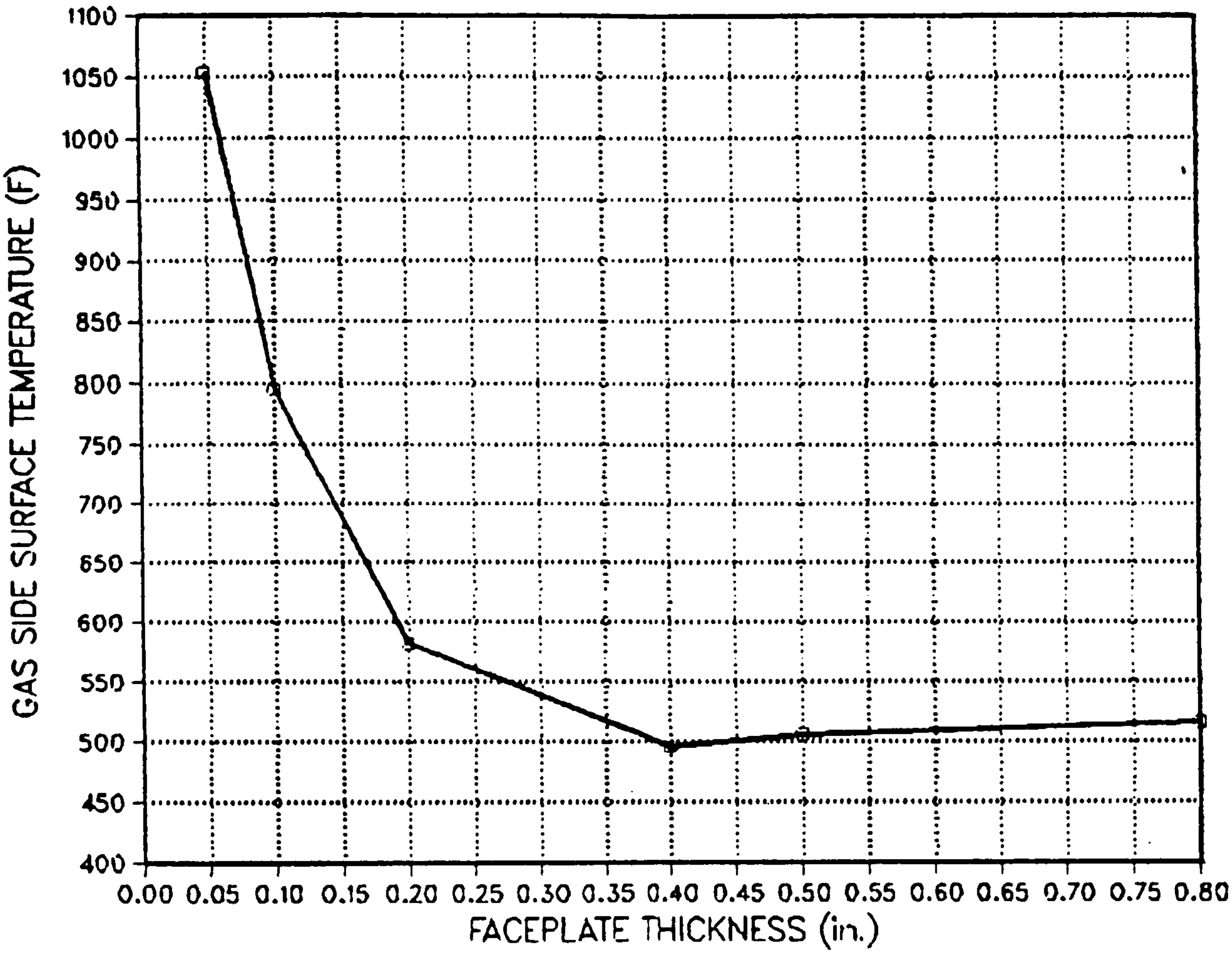


Figure 29. Helium Heater Injector Face Surface Temperature for Various Faceplate Thicknesses

a. Reactants Flow Rates and Throttling Range

Anticipated helium flow rates and inlet pressures and temperatures were provided by MMMSS as shown in Table I. The module ODE (One Dimensional Equilibrium) of the TRAN72 computer code (Ref. 5) was used to calculate the reactants (oxygen and hydrogen at 8 to 1 mixture ratio) to helium flow rate ratio required to provide the mixture temperature of 900°R. The ratio was calculated to be approximately 0.170 for the case where the inlet helium temperature is 40°R, and it is approximately 0.124 for the case where the inlet helium temperature is 300°R. The flow rate ratios were calculated assuming perfect combustion efficiency. Calculated oxygen and hydrogen flow rates, assuming 90 percent combustion efficiency, corresponding to the three helium flow conditions identified in Table I are shown in Table VI. The throttling range, which is the ratio of maximum to minimum flow rate, was calculated to be approximately 3.8 to 1.

b. Flammability Requirement

Flammability requirement of no more than 4 percent by volume of either of the reactants in the heater effluent was suggested by MMMSS. Calculation showed that failure to open of the oxygen valve will result in only approximately 4 percent by volume of hydrogen, and that failure to open of the hydrogen valve will result in only approximately 2 percent by volume of oxygen in the effluent gas. The calculation was made using the flow rates of oxygen and hydrogen shown in Table VI (assumed 90 percent combustion efficiency). Although, there is no combustion efficiency requirement, the goal has been set to be at 90 percent. Lower combustion efficiency would not only increase the primary heater oxygen and hydrogen tank sizes but also increase the amount of unburnt reactants in the effluent gas.

c. Chamber Sizing

The smallest chamber diameter satisfying the exit Mach number requirement from Table I ($M \leq .3$) was calculated to be approximately 2.8 in. The corresponding pressure drop was estimated to be approximately 30 psid. The chamber size calculation assumes the flow is one-dimensional. The pressure drop calculation assumes the flow is well-developed and uniformly mixed and without the turbulence

TABLE VI
Primary Heater Operating Point Conditions

	Design Conditions (Helium)		
	Maximum Flow Conditions	Minimum Flow Conditions	Critical Inlet Flow Condition
Heater Pressurant Inlet Condition			
Flowrate (lbm/sec)	30	11.4	22.8
Pressure (psia)	1550	1475	1550
Temperature (°R)	40	300	300
Heater Reactants Inlet Conditions			
Flowrate			
LO2 (lbm/sec)	6.07	1.59	3.18
LH2 (psia)	.76	.20	.40
Injector Inlet Pressure			
LOX (psia)	2820	1555	1885
LH2 (psia)	2820	1555	1885
Heater Conditions			
Chamber Pressure (psia)	1530	1460	1490
Mixture Ratio (O/F)	8.0	8.0	8.0
ERE (%)	90	90	90
Heater Outlet Conditions			
Total Flowrate (lbm/sec)	36.83	13.19	26.38
Bulk Temp, Stag (°R)	900	900	900
Temperature Uniformity (%)	5	5	5
Pressure, Stag (psia)	1450	1450	1450
Composition (mass fraction)			
He	95.0	96.5	96.5
H20	4.3	3.0	3.0
02	.2	.2	.2
H2	.5	.3	.3
OH	-	-	-
Other	-	-	-

ring. Thus, the exit Mach number and the pressure drop are probably underpredicted with these assumptions. Therefore, a larger chamber diameter, equal to 4.0 in., was selected to compensate for the underprediction and provide more margin for both the exit Mach number and pressure drop. The larger chamber diameter results in a lower exit Mach number and pressure drop but also less mixing between the combustion gases and the helium pressurant for a given length. Mixing analysis presented in Section VI,D,1 showed that a 20 to 1 length to diameter (L/D) ratio would provide adequate mixing, thus the chamber length was specified to be approximately 80 in. It should be noted that these chamber dimensions are subjected to changes and will be defined more definitely after a detail analysis is made to accurately calculate the pressure drop, and the radial profiles of the temperature, Mach number, and species concentrations at the exit.

d. Injector Pattern Design

The injector design must provide high efficiency, yet stable combustion for a large throttling range at constant combustor pressure. The high efficiency injector reduces not only the amount of reactants required and the tank size but the amount of unburnt reactants in the heater effluent gas used as pressurant for the downstream propellant tanks. A review of Aerojet O_2/H_2 element history showed that the Extended Temperature Range (ETR) program used a liquid oxygen and liquid hydrogen injector. Most other injectors use gaseous hydrogen with either gaseous or liquid oxygen. A list of Aerojet O_2/H_2 element history is provided in Table VII.

The ETR injector used like-on-like doublet elements with platelet face cooling. The combustion performance of this injector was found to be mixing limited. For the helium heater, the combustion performance will be adversely affected by the presence of the large amount of helium. Faster mixing and reaction of hydrogen and oxygen will reduce the adverse influence of the helium on combustion performance. Therefore, injector elements with higher intraelement mixing efficiency are more desirable.

Several element candidates were evaluated; the element design with two hydrogen streams impinging on the edges of the like doublet LOX fan was

TABLE VII
Aerojet H_2/O_2 Injector Element History

Program	Pc (psia)	Propellant State	Element Type	Total Flow Rate (lbm/sec)
ETR	250-500	GAS/LIQUID	SHEAR COAX	1.4 - 3.0
	240-500	LIQUID/LIQUID	EDM LIKE DOUBLET PAIRS W/PLATELET FACE COOLING	1.4 - 3.0
OAMS	CLASSIFIED	GAS/GAS	HIPERTHIN LIKE DOUBLETS	4.2
ITA	300	GAS/GAS	PLATELET I - TRIPLET	3.45
OTV	30-2000	GAS/GAS	PLATELET I - TRIPLET	0.09 - 6.25
XLR-134	500	GAS/LIQUID	SHEAR COAX	1.05

selected. Rationale for the selection is provided in Table VIII. The injector has six elements, the diameters of the oxygen and hydrogen orifices are 0.063 and 0.044 inch, respectively. Preliminary analysis, neglecting the effects of helium, showed that 90 percent combustion can be achieved within approximately 3.5 in. from the injector face. At all operating conditions, the normalized (by the chamber pressure) injector pressure drops for both oxygen and hydrogen circuits are above 6 percent, a value that has been shown historically to be adequate for chug stability. In addition, the relatively large residence time (long L*) and small combustion time lags (oxygen and hydrogen are highly volatile and reactive) will increase stability margin. Existing analytical tools for the prediction of combustion instability are not capable of accounting for the effects of the relatively large quantity of helium. It is expected that non-acoustic (Chug) as well as acoustic stability margin would be enhanced by the high flow rate of non-reacting helium. Technology acquisition in this area is recommended as discussed in the following section.

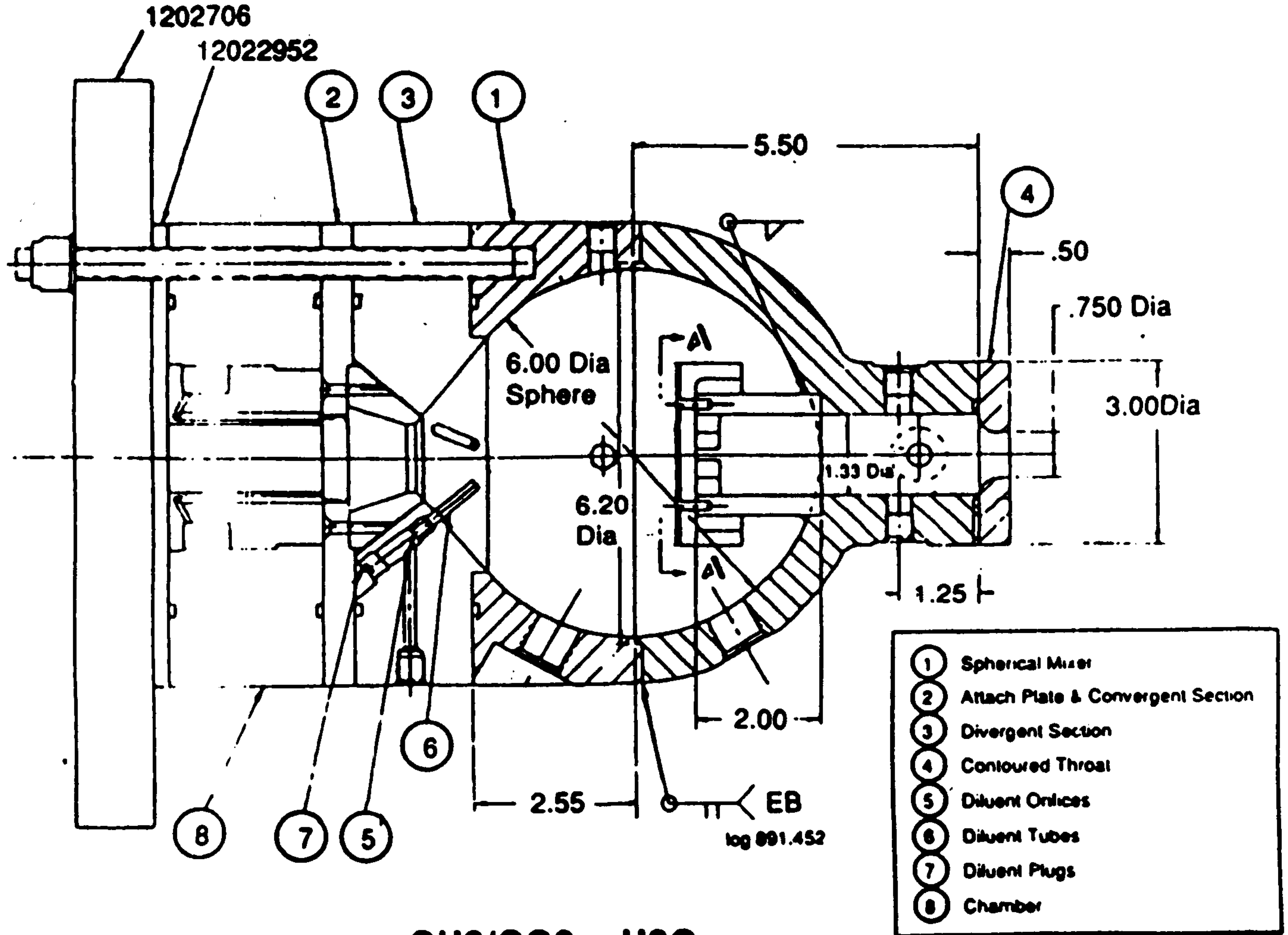
E. PRIMARY HEATER TECHNOLOGY ISSUES

The feasibility of using a stoichiometric combustor for direct heating of a diluent was demonstrated during an Aerojet 1989 IR&D program (Ref. 14). Well mixed and uniform temperature steam was produced using a simple and low cost heater/mixer shown in Figure 30. The heater consisted of an existing GO_2/GH_2 injector and a water regeneratively cooled combustor with discrete water diluent injection into a splash plate spherical mixer. The heater produced a peak thermal output of approximately 7500 Btu/sec while heating 4-6 lbm of water to 600 to 1400°F.

While a large data base of proven liquid propellant combustor technology is already in place, as noted in Table IX, the present level of technology has some shortcomings for application to the direct helium heating pressurization concept. A list of these shortfalls is provided in Table X. The primary heater technology demonstration program was focused to significantly extend this technology base in several areas. A list of these growth areas in technology, which were being addressed in this program, is provided in Table XI.

TABLE VIII
Element Selection Rational

- o OFO TRIPLET
  - HIGH UNIELEMENT EM
  - OX ON OUTSIDE MAY EFFECT VAPORIZATION AND/OR MIXING
- o FOF TRIPLET
  - GOOD UNIELEMENT EM
  - REQUIRES $D_o/D_f = 2$ FOR EQUAL ΔP
  - REQUIRES $\Delta P_o/\Delta P_f = 16$ FOR EQUAL D_j (GOOD ATOMIZATION)
- o CANTED LIKE DOUBLETS
  - FAIR INTER ELEMENT MIXING; REGIONS AWAY FROM UNLIKE IMPINGEMENT DON'T MIX WELL
  - GOOD MIXING REQUIRES REASONABLE ELEMENT DENSITY
- o SHOWERHEADS
  - POOR MIXING
- o UNCANTED OX DOUBLET WITH 2 SHOWERHEAD FUEL IMPINGING JUST ABOVE OX LIKE IMPINGEMENT POINT
  - SHOULD HAVE UNIELEMENT EM LIKE TRIPLETS
  - GOOD OX ATOMIZATION CHARACTERISTICS
  - FUEL ENCAPSULATING OX



GH2/GO2 + H2O

Figure 30. Direct Pressurant Heating Using a GOX/GH_2 Stoichiometric Combustor Has Been Demonstrated

TABLE IX

PROVEN TECHNOLOGY IS AVAILABLE FOR DIRECT PRESSURANT HEATING USING A STOICHIOMETRIC COMBUSTOR

- Gas/gas and liquid/liquid O_2/H_2 injectors
- Regeneratively cooled combustion chambers
- Acoustic damping devices (resonators and baffles) to insure combustion stability
- Elevated reactant inlet pressure to achieve deeper throttling
- Hypergolic and O_2/H_2 torch ignition
- Discrete pressurant injection spherical splash plate mixer
- CFD models with varying sophistication and application experience

TABLE X

PRESENT LEVEL OF TECHNOLOGY HAS SOME SHORTFALLS

Shortfalls	Responsible Technology Area
Higher cost and increased design complexity	Regeneratively cooled chamber, lower flowrate/ element injector and acoustic damping devices
Complex scaling	Injector combustion stability
Higher pressure drop	Regeneratively cooled chamber splashplate mixer
High inlet pressure requirements	Throttling fixed orifice injector
Uncertain ignition limits	O_2/H_2 torch igniter operating in a pressurized, cold, inert environment
Limited CFD modeling experience	Early attempts at using FLUENT identified modeling limitations

TABLE XI

TECHNOLOGY GROWTH ISSUES HAVE BEEN IDENTIFIED TO REDUCE OR ELIMINATE SHORTFALLS

Shortfall Improvement	Proposed Technology Growth
Lower cost and decreased design complexity	Use helium pressurant to provide combustor cooling and acoustic damping to extend combustion stability margin
Reduced scaling complexity	Large flowrate/element injector with inert helium to insure dynamic stability
Lower pressure drop	Eliminate regeneratively cooled chamber. Rely on a simple coaxial mixer with trip ring if necessary
Reduced inlet pressure	Improve chug stability model within an inert non-sonic environment
Define ignition limits	Conduct simple igniter testing within an inert, pressurized, cold environment to upgrade igniter design modeling
Expand CFD application	Apply FLUENT code with multi-phase real gas finite reaction options. Correlate with available data bases

A major portion of the technology improvement involved use of the large quantity of cold helium for improved stoichiometric combustor operation. Helium could be used for direct combustor cooling by injecting the helium so that it provides a protective barrier between the hot stoichiometric combustion gases and the combustion chamber walls. This would eliminate the requirement for a conventional regenerative/dumped cooled chamber thus reducing fabrication cost and complexity, minimizing helium circuit pressure drop, and improving safety and reliability. The technology development in this case involves investigation of the effects of the helium on the stoichiometric combustor efficiency and mitigation of these effects through injector element design.

It is hypothesized that the presence of an inert gas barrier at the perimeter will also be beneficial from a combustion stability standpoint. This barrier could provide compliance and damping to the system thus producing stable combustion without the use of complex and higher risk acoustic damping devices. It is also possible that the chug stability limits could be extended through the use of the helium barrier thus extending the heater operational capability and reducing the LOX/LH_2 inlet pressure requirements to the heater.

The approach for technology improvement is this area was to utilize existing hardware and designs (e.g., the Extended Temperature Limits, ETR thrust chamber) to conduct simple small scale hot-fire tests. The test results would be used to extend existing combustion stability models to better characterize combustion stability with large inert barriers.

Similarly, the effects of ignition within a cold, pressurized, inert gas environment would be investigated using an existing LO_2/LH_2 torch igniter. Igniter power requirements, spark plug design, and ignition sequencing and ignition propagation would be experimentally investigated.

Finally, CFD modelling of the combustion and mixing processes would be extended through the application and verification of existing CFD codes. The FLUENT code, described in Section IV,D,1 is a typical example of an existing CFD code and has been applied with some success in this study. Extension of FLUENT using real gas properties and finite reaction rates is required. Verification of the model results is also recommended using existing test data such as AEDC coaxial flow results (Ref. 6), Biler's hydrogen/air test results (Ref. 7) and Aerojet/NASA's Film Cooling Effects data (Ref. 10).

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